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Enhanced Emergency Smoke Venting

FAA Technical Center
Atlantic City International Airport
N.J. 08405

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Final Report

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16. Abstract

This study evaluated two concepts for modifying the air conditioning systems of large commercial airplanes to enhance the venting of smoke that may be continuously injected into the passenger cabin during inflight fire emergencies. Data from past fire accidents and airplane tests provided a basis for creating four fire/smoke scenarios and deriving five sets of equations to predict the smoke venting effectiveness of current airplanes and the proposed concepts. Concept A would modify the air conditioning packs by adding high flow modes with dual outflow valves and Concept B would add ram air ventilation with an added dump valve. The estimated costs to incorporate Concept A or B in the U. S. fleet were about $381 million or $587 million, respectively. The effectiveness equations predicted that both concepts would provide only slightly significant smoke venting enhancement. Furthermore, the study showed that both concepts would have been negated by the reported crew actions and/or fire damage in past fires. It was concluded that current U. S. fleet airplanes will provide a majority of the passenger cabin free of smoke during inflight fires while the air conditioning systems are kept operating.

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EXECUTIVE SUMMARY

This study evaluated two concepts for modifying the air conditioning systems of large commercial airplanes to enhance the venting of smoke that may be continuously injected into the passenger cabin during an inflight fire emergency.

The study included a search for pertinent data from FAA regulations, advisory circulars and correspondence, test standards, certification tests, non-certification tests, past fire accidents and airplane emergency procedures. As presented in Section 2, there are no FAA regulations applicable to the subject but some non-certification test data and past fire data were found to support the derivation and partial validation of equations to predict smoke venting performance.

As a basis for evaluating the proposed concepts, four fire/smoke scenarios were created to define and quantify the emergency smoke conditions. As presented in Section 3, these scenarios are 1: smoke only in the mid cabin ceiling, 2: smoke/fire in the aft cabin ceiling, 3: smoke/fire in an aft lavatory and 4: fire/smoke in the forward cabin.

The two enhancement concepts, called Concept A (air conditioning pack high flow mode with dual outflow valves) and Concept B (ram air ventilation with added dump valves), are described in Section 4. The estimated costs to incorporate Concept A or B in the U. S. fleet were about $381 million or $587 million, respectively.

Five sets of equations were derived to define and calculate a smoke venting effectiveness "parameter" for all of the concepts, scenarios and airplanes in this study. As presented in Section 5, these equations will predict the concentration and length of the smoke cloud in the passenger cabin and are partially validated by the results of past fires and airplane tests.

Using the equations from Section 5, the current airplane configurations and the Concept A and B configurations from Section 4 have been analyzed to predict the effectiveness during the scenarios from Section 3. The analysis results are presented in Section 6 for each case along with grouped and averaged results. The analyses predict that Concept A would provide only small improvements in smoke venting; e.g., the average percentage of the passenger cabin that is free of smoke would improve to 82.5 % compared to 77.8% for current airplanes during cruise. The predictions for Concept B are similarly small for all but ground operations with engines OFF; in this case Concept B would improve the average smoke cloud concentration to 0.000035 lb/cu ft compared to 0.00045 lb/cu ft for current airplanes.

Based on the understanding of the past fire accidents and the smoke venting predictions provided by this study, the main conclusions are:

- Both proposed concepts would provide only slightly significant smoke venting improvement compared to current airplanes.
- The improved smoke venting predicted for both concepts would have been negated by the reported flight crew actions and/or the fire damage in the past fire accidents on the Varig 707, Saudi L-1011 and Air Canada DC-9 airplanes.
- During inflight fires similar to the past fires on the Varig 707, Saudi L-1011 and Air Canada DC-9 airplanes, a majority of the passenger cabin length is predicted to be free of smoke while the air conditioning systems of the current U.S. fleet are kept operating.

1. INTRODUCTION

This report presents the results of the study for Enhanced Emergency Smoke Venting conducted by The Boeing Company for the FAA Technical Center under Contract No. DTFA03-87-C-00038. As required by the contract, the study evaluated two concepts for modifying the air conditioning systems of large commercial airplanes to enhance the capacity for the venting of smoke that may be continuously injected into the passenger cabin during an inflight fire emergency. As required by the Request for Proposal, the two concepts were proposed and selected before the contract award.

2. DATA SYNOPSIS

2.1 FAA REGULATIONS, ADVISORY CIRCULARS AND CORRESPONDENCE

A review of current Federal Aviation Regulations (FARs) has revealed that they do not include requirements for the evacuation of continuously generated smoke from cockpits or passenger cabins during in-flight fires. The only regulation related to smoke evacuation from an occupied volume of the airplane is FAR 25.831(d) which reads:

> "If accumulation of hazardous quantities of smoke in the cockpit area is reasonably probable, smoke evacuation must be readily accomplished, starting with full pressurization and without depressurizing beyond safe limits."

This regulation is not applicable to this study because (1) it relates to the cockpit rather than the passenger cabin and (2) it has been interpreted to require evacuation after limited duration smoke generation rather than during continuous smoke generation. This limited duration smoke interpretation has been used in the certification tests on all past airplanes and is still prescribed for current certifications in Paragraph 9.e.(1) (ii) of Advisory Circular 25-9[1].

A search for FAA/Boeing correspondence from 1970 through the present has been conducted by Boeing Airworthiness Offices in both Renton and Everett. The search disclosed at least 26 letters between Boeing and the FAA on the subject of smoke; the only letter pertaining to smoke evacuation from passenger cabins observed that passenger cabin smoke evacuation testing was not required for certification. Seven (7) of the letters related to the Multiple Expert Opinion Team (MEOT) of airplane manufacturers and FAA personnel that worked from 1975 until about 1978 to develop improved smoke certification test standards for cockpits and cargo compartments; these standards were the primary basis for the guidelines eventually released as Advisory Circular 25-9.

2.2 TEST AND VENTILATION STANDARDS

A review for test standards has not revealed any standardized test procedures applicable to passenger cabin smoke evacuation. Cockpit smoke evacuation testing is covered in Paragraph 8.16.1 of D6-1744 [2]. The testing procedures presented are essentially the same as those in Advisory Circular 25-9. Some special (non-standardized) procedures for testing passenger cabin smoke evacuation are described in Paragraph 2.4.

There are no standards for passenger cabin ventilation rates. FAR 25.831 requires ventilation for occupied compartments but does not specify flow rates for passenger cabins. The Society of Automotive Engineers publishes a relevant Aerospace Recommended Practice ARP 85 entitled "Air Conditioning Systems for Subsonic Airplanes" (revision E currently in work). This ARP is not used as a "standard" but does provide guidelines for establishing ventilation rates based on specific airplane variables such as air distribution/stagnation, smoking zones and temperature control requirements. Past airplanes have provided widely differing ventilation rates to accommodate specific airplane variables.

2.3 CERTIFICATION TESTS

A review of past airplane FAA-required certification testing by Boeing and Douglas has revealed no tests demonstrating the evacuation of continuously generated smoke from passenger cabins; this is

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[1] FAA Advisory Circular 25-9, "Smoke Detection, Penetration and Evacuation Tests, and Related Flight Manual Emergency Procedures", dated 7-29-86

[2] Boeing Document D6-7144, "Flight Test Technical Manual - Vol. II" dated 7-25-80

consistent with the absence of requirements for such tests (see Paragraph 2.1). Some Boeing airplane certification programs have included tests using limited duration smoke generation to demonstrate the proper functioning required by FAR 25.1301(d) of the galley and lavatory exhaust systems. When the smoke from these tests spread into the passenger volume, it was shown to be evacuated by the normal operation of the cabin air conditioning system.

2.4 NON-CERTIFICATION TESTS

Some non-certification testing has been conducted with continuous smoke generation in passenger cabins on various airplane models and some of these tests are pertinent to this study. The report of these tests on Boeing 707 airplanes was provided to the FAA [3]. This test used two 707-321C airplanes in three configurations (all-cargo convertible, all-passenger convertible and "stripped" freighter) to evaluate 41 operating conditions and many special procedures during cruise and descent flight with continuous and limited duration smoke generation from mineral oil and tobacco smoke generators. One of the significant conditions was with the test airplane cruising at 10,000 ft. altitude with 0.3 psid cabin pressure differential and three (3) turbo compressors and two (2) air conditioning packs operating. A TMI Cloud Maker smoke generator was continuously generating smoke in the aisle in front of the aft lavatories. These conditions resulted in a steady-state, smoke-free cabin forward of the aft four (4) rows of passenger seats. At that time the forward outflow valve was closed while maintaining all other conditions; this resulted in the smoke cloud moving aft beyond all of the passenger seats into the lavatory aisle area.

The 727 test [4] used a leased Braniff 727-100 QC airplane in four configurations (all cargo, mixed passenger cargo with barrier at two stations and all passenger) to evaluate 20 operating conditions and many special procedures during cruise and descent flight with continuous smoke from a mineral oil smoke generator. One condition especially pertinent to this study was with the airplane cruising at 25,000 ft on two air conditioning packs with maximum cabin differential while continuously generating smoke in an aft lavatory. This condition resulted in no smoke in the passenger cabin, in the opposite lavatory or in the stowage bins during 7.5 minutes of operation with the lavatory gasper either on or off. At this time, the smoke generator was moved into the aisle between the two aft lavatories which caused a "very dense" smoke cloud to stabilize over the aft 6 seat rows with "hazy" smoke over the next 6 seat rows in the next 5.5 minutes. This condition was stable for the next 2.5 minutes at which time one air conditioning pack was turned off. This action caused the smoke to move forward in the cabin with "wisps" of smoke spreading into the cockpit after 5.5 minutes. One minute later, both packs were turned on and the cabin altitude increased to 10,000 ft. This action resulted in clearing all smoke from the airplane forward of the aft 6 seat rows. This smoke cloud position remained constant for the next 4.0 minutes while a descent to 10,000 ft and a simulated approach were conducted.

The 737 test [5] used an Aer Lingus 737-200C airplane in four configurations (all cargo, all passenger and two mixed passenger - cargo) to evaluate 21 operating conditions and many special procedures during cruise and descent flights with continuous and limited duration smoke from a mineral oil smoke generator. One condition pertinent to this study was with the airplane cruising at 25,000 ft. on two air conditioning packs with maximum cabin pressure differential while continuously generating smoke in the aft lavatory. This condition resulted in no smoke in the passenger cabin during 9.0 minutes of operation. When both the gasper was turned on and the lavatory door cracked open, the smoke spread forward over the next 6.0 minutes to a stable density profile that varied from "light" smoke at the 10th seat row from the aft to "very heavy" at the aft lavatory/galley area. This smoke profile remained

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[3] Boeing Letter B-7670-RA-4511, "Test Report of Smoke Evacuation, Model 707-300C", dated 5-13-74

[4] Boeing Document D6-7771, Section 3.10.109, "Smoke Evacuation - Continuous Smoke Generation", dated 4-1-75

[5] Boeing Document D6-24261, Section 3.10.031, "Smoke Evacuation - Continuous Smoke Generation", dated 5-13-75

stable when one pack was turned off for the next 6.0 minutes, but the smoke inexplicably moved farther forward and became more dense when both packs were again turned on.

2.5 PAST FIRE ACCIDENTS

A review of past fire accidents on passenger flights that ended in safe landings or survivable crash landings has revealed three cases in which fatalities were reportedly caused primarily by smoke in the passenger cabin.

2.5.1 VARIG 707 AT PARIS ON 7-11-73

The Boeing 707 with 134 people on board, was approaching Paris-Orly after an 11 hour flight from Rio de Janeiro. When the plane was descending through about 8,000 feet a passenger told one of the flight attendants that the lavatory was full of white smoke. Smoke eventually reached the cockpit reducing visibility to the point that the instruments were unreadable. The airplane landed in a field short of the airport. After a ground run of 400 to 500 meters the plane came to rest. Nine members of the crew (one of which later died) escaped through the cockpit sliding windows and one each went out the forward doors. One passenger was rescued from the forward part of the aircraft by crash - fire - rescue personnel. The rest of the passengers and crew died. One steward observed that many of the passengers had passed out during the descent and most were found strapped in their seats.

The status of the air conditioning system during the descent and landing is not known. However, the French government final report[6], states that the emergency procedure for smoke originating from the air conditioning system was being carried out. The final report also states that the post - accident examination of the flight engineer's panel revealed the following:

Turbo compressor controls 2, 3 and 4:	NORMAL	
Bleed air control:	1 AND 3	ON
	2 AND 4	OFF
Wing isolation valve control:	LEFT	OFF
	RIGHT	ON
Ram air intake control:	OFF	
Air conditioning packs:	OFF (BOTH)	
Thrust recovery control valves:	OFF	
Mixture control valves:	MANUAL	

> Note: These control positions do not completely correspond to the procedure for smoke originating from the air conditioning system. However, since the report is based on crew interviews it is assumed for purposes of this study that the procedure was used, at least in the early stages of the fire. The listed control positions show both packs OFF which probably was the situation for approximately the last 2.5 minutes before the crash landing (see time line below).

The final report identified above and the survivor's interviews found in the Paris fire department Survey Report[7] have been studied to derive an estimated time line and more thoroughly estimate the influence of the air conditioning system on the passenger cabin smoke.

[6] Board of Inquiry Final Report entitled "Accident Involving the Boeing 707 PP-VJZ of the Varig Company (SAULX-les-CHARTREUX July 11, 1973)", dated December 1975

[7] Survey Report by the Chief of Battalion, Paris Fire Brigade entitled "Fire of the Boeing 707 Belonging to Varig Brazilian Company on July 11, 1973"

TIME LINE
(Minutes)

0	Smoke discovered
0 to 2.5	Smoke cloud contained aft of the passenger seats in the galley and lavatory aisle area.
2.0 to 3.0	Flight crew began the air conditioning smoke procedure which reduced the cabin ventilation about 50%.
3.0	Smoke cloud began moving forward into the tourist class seating area.
4.0	Two crew members entered the cockpit to report the increasing seriousness of the situation. This time corresponds to the second and last radio message about the fire. It is assumed that all cabin ventilation was stopped at this time in response to the crew members' report to the cockpit.
5.0	Smoke came forward of the class divider at approximately the wing leading edge.
5.2	Smoke entered cockpit.
6.0	Cockpit windows were opened but the action caused more smoke inflow to the cockpit.
6.5	Airplane crash landed.

2.5.2 SAUDI L-1011 AT RIYADH ON 8-19-80

The Lockheed L-1011 with 301 people on board returned to Riyadh, Saudi Arabia when an uncontrolled fire developed in the lower aft cargo compartment 6.9 minutes after takeoff. The airplane landed 21.5 minutes later but did not make a maximum stop landing on the runway with immediate evacuation. The airplane taxied clear of the runway and came to a stop on an adjacent taxiway 2.65 minutes after touchdown. While parked on the taxiway, the airplane's engines continued to run for 3.25 minutes. Approximately 22.7 minutes after engine shutdown, ground personnel managed to open a door and found none of the occupants alive. The fire intensified and destroyed the airplane.

The following time line has been taken from the cockpit voice recorder (which stopped 3 seconds before touchdown) and other data in the Saudi Civil Aviation final report:[8]

TIME LINE
(Minutes)

0	Visual and aural warning in cockpit of smoke in aft (C3) cargo compartment Flight engineer goes aft to investigate
5	Flight engineer returns reporting smoke in the aft cabin
7	Crew turns back for Riyadh
9	Two more smoke alarms received
11	Flight attendant reports that fire has invaded cabin in the aft cabin near the L4 door

[8] Presidency of Civil Aviation, Jeddah, Saudi Arabia document entitled "Aircraft Accident Report, Saudi Arabian Airlines, Lockheed L-1011, HZ-AHK, Riyadh, Saudi Arabia, August 19, 1980", dated 1-16-82

12 Fighting amongst passengers in aisles reported

14 Cabin reported as filled with smoke in the back
Another cargo area smoke alarm received

17 Aft duct overheat warning received. Post event investigation showed no damage to ducts

19 Flight attendants demonstrate and order impact brace position

20 Another smoke alarm received

21.5 Aircraft touchdown

Air conditioning packs shut down
Investigation showed pack shut down within 2 minutes after touchdown

24.2 Aircraft stopped after rolling out full length of runway and onto taxiway

25.7 Last radio transmission from aircraft

27.4 Engines shut down

50.1 Door opened from outside

This timeline shows that there was considerable activity in the cabin area up to and after touchdown. This indicates that the air conditioning, which was kept running, maintained a somewhat habitable atmosphere for more than 20 minutes even while an active fire burned in the cabin for half of that time.

The Saudi final report states that the cabin conditions became unsurvivable when the air conditioning packs were shut down which reportedly caused the increases of smoke and toxic gas concentrations that were inhaled and found in the lungs and blood samples of the victims.

2.5.3 AIR CANADA DC-9 AT CINCINNATI ON 6-2-83

This accident involved a Douglas DC-9 with 46 people on board and is described in the U.S. NTSB final report[9] from which this summary is drawn. About 1903, eastern daylight time, while en route at flight level 330 (about 33,000 feet m.s.l.), the cabin crew discovered smoke in the left aft lavatory. After attempting to extinguish the hidden fire and then contacting air traffic control (ATC) and declaring an emergency, the crew made an emergency descent and ATC vectored the airplane to the Greater Cincinnati International Airport, Covington, Kentucky.

At 1920:09, eastern daylight time, the airplane landed on runway 27L at the Greater Cincinnati International Airport. As the pilot stopped the airplane, the airport fire department, which had been alerted by the tower to the fire on board the incoming plane, was in place and began firefighting operations. Also, as soon as the airplane stopped, the flight attendants and passengers opened the left and right forward doors, the left forward overwing exit, and the right forward and aft overwing exits. About 60 to 90 seconds after the exits were opened, a flash fire engulfed the airplane interior. While 18 passengers and 3 flight attendants exited through the forward doors and slides and the three open overwing exits to evacuate the airplane, the captain and first officer exited through their respective

[9] National Transportation Safety Board Report No. NTSB/AAR - 84/09 entitled "Aircraft Accident Report - Air Canada McDonnell Douglas DC-9-32, C-FTLU, Greater Cincinnati International Airport, Covington, Kentucky, June 2, 1983", dated 8-8-84

cockpit sliding windows. However, 23 passengers were not able to get out of the plane and died in the fire. The airplane was destroyed.

During this fire electrical malfunctions occurred. One system affected was pressurization and air conditioning. Loss of electrical power to the ECS failed the augmentation valves to the closed position resulting in the unavailability of high pressure engine bleed air (i.e. fresh air) ventilation to the cabin. This was not apparent as the engines were still at cruise settings and fresh air entered the cabin normally from the low pressure engine bleed ports. When the throttles were retarded and the descent begun, several passengers noted that fresh air was no longer coming out of the overhead vents confirming the loss of the high pressure bleed air although this was not realized by the crew. The level of smoke in the cabin increased significantly at this point and it advanced forward through the cabin. It was thickest at the ceiling and reached to the floor. The smoke also entered the cockpit as the first officer had left the door open so as to facilitate communications with the cabin crew. Visibility in the cockpit was quickly reduced and the captain experienced difficulty reading the instruments. He was wearing smoke goggles but the first officer was not as he had left his pair aft. He did not use the third, spare pair located on the flight deck.

At about 3,000 feet the aircraft was depressurized in preparation for landing. The first officer also, about 4 minutes before touchdown, turned off the air conditioning packs under the mistaken belief they were feeding the fire. This, combined with the loss of the augmentation valves and the fact that ram air was never turned on, virtually eliminated the flow of fresh air into the cabin.

The final report identified above has been studied to estimate a time line and more thoroughly estimate the influence of the air conditioning system on the passenger cabin smoke.

TIME LINE (Minutes)	
-5	Fire begins in aft part of aircraft
0	Smoke discovered in aft lavatory by flight attendant
+2.5	Fire reported to captain
5	Electrical malfunction Loss of high pressure bleed
9	Begin descent Loss of fresh air in cabin Smoke increases
16	Packs off
20	Touchdown

2.6 EMERGENCY PROCEDURES

A review of the emergency procedures prepared by the manufacturers for smoke evacuation from passenger cabins has revealed similar procedures for Boeing, Douglas and Lockheed airplanes. All of these airplanes have multiple fire/smoke emergency procedures available which requires the crew to select the proper procedure on the basis of the type or location of the fire or smoke source or the flight conditions. All of the passenger cabin smoke evacuation procedures call for operating all available air sources or air conditioning packs such that maximum fresh air is supplied to the cabin. For all airplanes except the Boeing 757, the procedures call for the cabin altitude to be increased to about

10,000 ft. The procedures call for turning off any cabin air recirculation fans for all airplanes except the Boeing 747; the 747 procedure calls for the supplemental vent fans (if installed) to be off and the recirculation fans to be on to aid in smoke dilution. The Boeing 747 and the Douglas DC-8 and DC-9 airplanes have procedures available for partially opening one or more doors to evacuate smoke but some airlines have omitted or deleted door opening from their manuals.

2.7 DISCUSSION AND CONCLUSIONS

Based on the reported information from past accidents and data from Boeing flight tests, it is possible to reach certain conclusions relative to the air conditioning system and the cabin smoke concentrations that have reportedly caused fatalities.

In the Varig 707 accident (Paragraph 2.5.1) the air conditioning system was successfully controlling the smoke until the ventilation flow was reduced to about 50% by the flight crew action between 2 and 3 minutes after the smoke was discovered. This is consistent with the tests described in Paragraph 2.4. During the 707 test, normal 2 pack, 3 turbo compressor inflow contained the continuously generated smoke to the aft-most 4 seat rows. It is also similar to the 727 test where turning off one of the two air conditioning packs allowed smoke continuously generated just forward of the aft lavatory to move throughout the passenger cabin and inject wisps of smoke into the cockpit. This situation was caused by the 50% ventilation reduction as confirmed by the fact that a mostly smoke-free cabin condition was restored when both packs were again turned on.

In the Saudi L-1011 accident (Paragraph 2.5.2) the air conditioning system was successfully controlling the smoke until all of the packs were shut off by the flight crew within 2 minutes after touchdown.

In the Air Canada DC-9 accident (Paragraph 2.5.3) the air conditioning system was successfully controlling the smoke until about 9 minutes after the fire was discovered when the cabin ventilation stopped because the engine power was reduced for descent and the high stage bleed valves were closed by a fire-caused electric power failure. This situation caused severe but survivable smoke concentrations that would probably have improved when engine power was increased during approach and landing except for the fact that the flight crew turned both packs off about 4 minutes before touchdown.

3. FIRE/SMOKE SCENARIOS

3.1 GENERAL

All of the scenarios created for this passenger cabin smoke study share several common assumptions. Each scenario begins with the airplane in cruise at the maximum certified altitude at a mid-route position such that the distance to the nearest airport is one-half of the airplane range capability. The cabin temperature is 75° F with normal ventilation, the cabin altitude is 8,000 feet and 95% of the passenger seats are occupied. It is assumed that the smoke source is inaccessible to the occupants of the airplane and that the location of the smoke injection into the passenger volume does not change appreciably during the scenario. The smoke source's inaccessibility means that it cannot be eliminated with a fire extinguisher and that the air conditioning flow patterns do not directly ventilate the smoke source or spread the fire. It is further assumed that the original smoke source and/or other involved materials do not self-extinguish so that the smoke injection into the passenger cabin continues for the remainder of the scenario. It is assumed that the smoke and the venting procedures will not constrain the pilots choices of flight profile, altitude, airspeed and airport selection. The scenarios continue through the passenger evacuation which is assumed to be completed two minutes after the airplane is stopped and the engines are shut down. The incoming smoke has a smoke particle concentration of 0.00045 lb/cu. ft. which corresponds[10] to light transmissivity of about 1.7% over a 1-foot path. This smoke concentration was chosen to match the output of TMI Cloud Maker mineral oil smoke generators as calculated from Boeing calibration test data. The calibration tests involved operating the generators in a closed volume and measuring the time required to reduce the light transmissivity to 40% over a 3-foot path as measured with a laser densiometer. The transmissivity was converted to smoke concentration and used with the above data to calculate the concentration at the outlet of the TMI generator. The incoming smoke concentration and the smoke inflow rates given for each scenario are intended to represent situations that would rapidly spread smoke throughout the passenger cabin if the air conditioning flow were to be reduced or stopped. It is assumed that the fire does not incapacitate the air conditioning or cabin pressurization systems. Descriptions of the destructive effects on other aircraft systems are not included because the speculations on the possible effects would be virtually endless and beyond the scope of this study.

3.2 SCENARIOS

3.2.1 SCENARIO 1: SMOKE ONLY IN MID CABIN CEILING

A non-fire smoke source causes smoke at about 75° F to enter the passenger volume at the ceiling center line along the center 20% of the passenger cabin length. The smoke inflow increases during the initial 60 seconds of the scenario and continues at 200 cfm for the rest of the scenario. A passenger detects the incoming smoke and reports it to a flight attendant 30 seconds after the start of the scenario. Within the cabin, the neutrally buoyant smoke spreads slowly until it reaches an inflow jet from the air conditioning system. It then spreads quickly (60 seconds or less) through the height and width of the cabin and slowly through the length of the cabin depending on the air flow patterns of the air conditioning system.

3.2.2 SCENARIO 2: FIRE/SMOKE IN AFT CABIN CEILING

A smoke source injects hot, buoyant smoke into the passenger volume at the left side of the ceiling above the stowage bin. The smoke inflow is 300 cfm for the first 60 seconds of the scenario; it

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[10] The equation for this correspondence is $\log(100/T) = kCL$; where log = logarithm to the base 10, T = light transmissivity (% over path L), k = light obscuration coefficient (sq ft/lb) = 3906.0 for typical interior materials, C = smoke concentration (lb/cu ft) and L = length of light path (ft).

decreases for the next 60 seconds and continues at 200 cfm for the rest of the scenario. A passenger detects the incoming smoke and reports it to a flight attendant 10 seconds after the start of the scenario. Within the cabin, the hot, buoyant smoke tends to rise and remain against the ceiling and spread slowly laterally until it reaches an inflow jet from the air conditioning system. It then spreads quickly (60 seconds or less) through the height and width of the cabin and slowly through the length of the cabin depending on the air flow patterns of the air conditioning system.

3.2.3 SCENARIO 3: FIRE/SMOKE IN AFT LAVATORY

A smoke source injects hot, buoyant smoke into the passenger volume at the top of the aft lavatory partition on the airplane center line. The smoke inflow increases during the initial 5 minutes of the scenario and continues at 200 cfm for the rest of the scenario. A passenger detects the incoming smoke and reports it to a flight attendant 2 minutes after the start of the scenario. Within the cabin, the hot, buoyant smoke tends to rise and remain against the ceiling and spreads slowly until it reaches an inflow jet from the air conditioning system. It then spreads quickly (60 seconds or less) through the height and width of the cabin and slowly through the length of the cabin depending on the air flow patterns of the air conditioning system.

3.2.4 SCENARIO 4: FIRE/SMOKE IN FORWARD CABIN

A smoke source injects hot, buoyant smoke into the passenger volume through the floor level return grilles on the right side of the airplane at the front end of the passenger cabin. The smoke inflow increases during the initial 60 seconds of the scenario and continues at 200 cfm for the rest of the scenario. A passenger detects the incoming smoke and reports it to a flight attendant 30 seconds after the start of the scenario. Within the cabin, the hot, buoyant smoke tends to rise along the cabin sidewall and spreads slowly laterally until it reaches an inflow jet from the air conditioning system. It then spreads quickly (60 seconds or less) through the height and width of the cabin and slowly through the length of the cabin depending on the air flow patterns of the air conditioning system.

4. ENHANCEMENT CONCEPT DESCRIPTIONS AND COST ESTIMATES

4.1 GENERAL

This contract required study of two concepts for airplane modifications to enhance the capacity for the emergency venting of smoke that is being continuously injected into the passenger cabin during inflight fires. This report section repeats the general outline of each concept from the contract proposal and follows with the requirements, objectives, descriptions and cost estimates for incorporating both concepts in Boeing 707, 727, 737, 747, 757 and 767 and Douglas DC-8, DC-9/MD-80 and DC-10 airplanes. The Lockheed L-1011 is similar to these airplanes; it has three air conditioning packs like the DC-10 and forward and aft outflow valves like the 707.

The cost estimates are intended only for scoping the impact of the changes on the industry. They were obtained without benefit of detailed engineering definition. The costs are not to be considered a commitment to supply or sell any products or services. It is recommended that these estimates be used only for indication of the total fleet approximate cost impact and not on a model by model basis, due to the inherent variation in scoping estimates.

The numbers of airplanes presented as "current U. S. fleet" are the inventories of all U. S. airlines at year-end 1987 and the numbers called "future production" are forecasts of total production for 1988 through 1992. The current fleet numbers for Boeing, Lockheed and Airbus models are from World Jet Airplane Inventory [11] which also presents annual delivery rates that were extended to forecast future production of Airbus models. Future production of Boeing models was provided by the Boeing Market Analysis Organization. The current U. S. fleet and future production numbers for Douglas models were provided by the manufacturer.

The approximate airplane weight increases are estimated to be in the range of 50 to 100 pounds for Concept A and 200 to 400 pounds for Concept B.

4.2 CONCEPT A: PACK HIGH FLOW WITH DUAL OUTFLOW VALVES

4.2.1 OUTLINE FROM PROPOSAL

Concept A (see Figure 4.2.1-1) provides for immediate action to enhance smoke clearance and provides for directional control of smoke evacuation. This concept involves adding a high-flow operating mode to the air conditioning packs and a second cabin pressure control outflow valve at the opposite end of the airplane from the current outflow valve. Increased cabin ventilation will accelerate smoke removal. The second outflow valve will allow the cabin axial airflow to be directed toward the smoke source and away from the passengers. This concept will be operable from the time smoke starts until the engines are stopped after landing.

The operation of Concept A is shown for a hypothetical case on Figure 4.2.1-1. It shows an inextinguishable smoke source assumed to be located in the forward passenger cabin and generating smoke at a rate such that the normal air conditioning would not prevent the smoke cloud spreading into a large fraction of the passenger cabin. The altitude vs time profile shows the time labeled "smoke" when the crew initiates the enhanced smoke venting operation by (1) switching the air conditioning packs to high flow mode and (2) transferring the cabin pressure control to the forward outflow valve. The high pack flow will provide increased smoke-free air for the passengers to breathe and also create high, forward-directed axial flow velocity in the passenger cabin to push the smoke cloud toward the source and away from the passengers. If the smoke source is in the aft half of the cabin, the aft

[11] Boeing document "World Jet Airplane Inventory at Year - End 1987", by the Market Analysis Organization, dated March 1988.

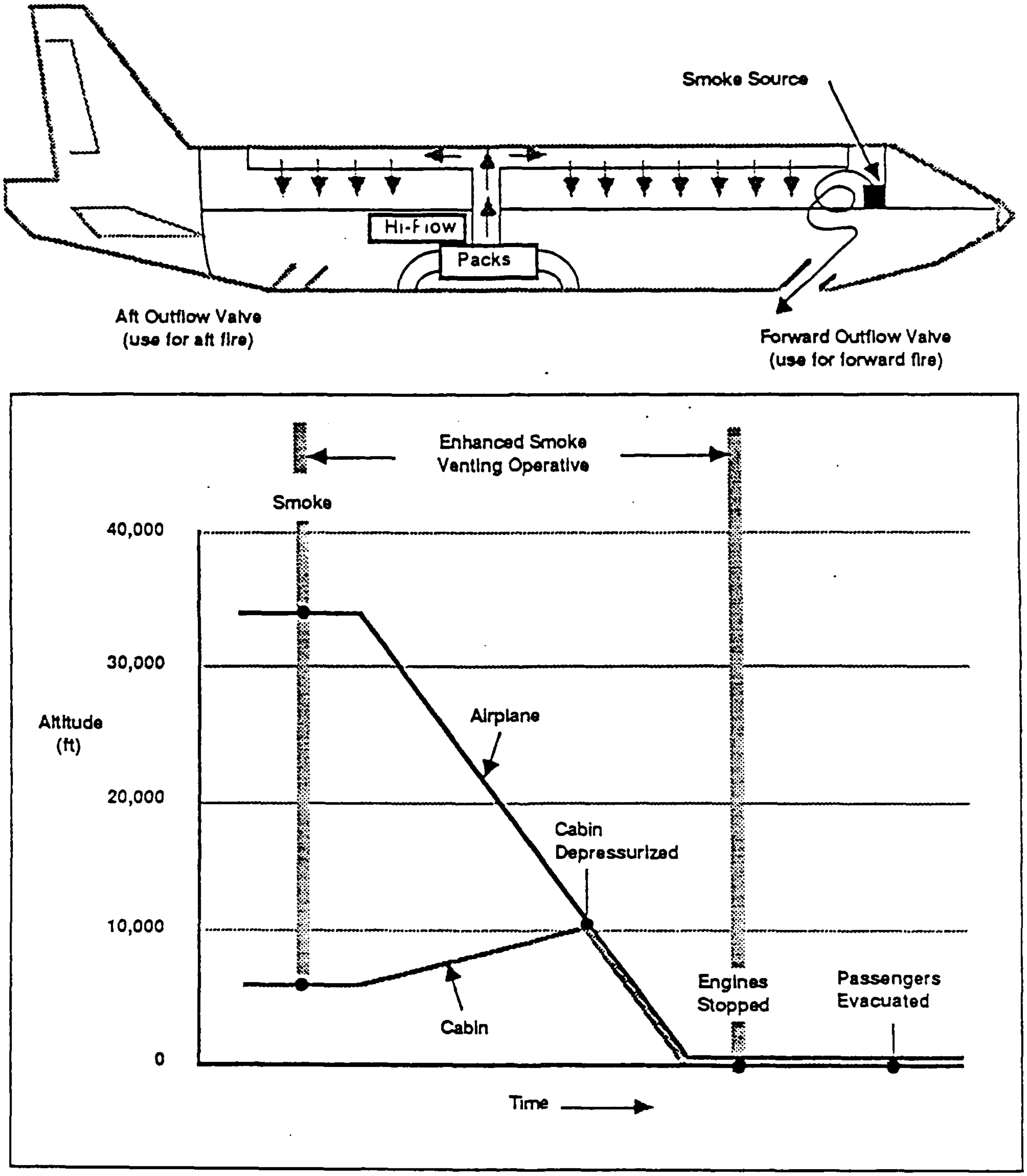


FIGURE 4.2.1-1. CONCEPT A: PACK HI FLOW VENTILATION WITH DUAL OUTFLOW VALVE

outflow valve would be used to push smoke in the opposite direction by creating aft-directed axial flow. With this concept, the cabin pressure may be controlled on a normal profile or gradually depressurized as shown on Figure 4.2.1-1. In either event, the axial flow velocity will increase as the cabin is depressurized because the portion of pack inflow flowing through the outflow valve increases to 100 percent while the leakage and other outflows decrease to zero. The enhanced smoke venting will cease to operate when the engines (which are the source of pack airflow) are stopped at the time labeled "Engines Stopped" on the figure. This total stoppage of ventilation means that the passengers will be exposed to rapidly increasing smoke in the cabin while they are evacuating the airplane.

4.2.2 CONCEPT A: REQUIREMENTS AND OBJECTIVES

The flow objective for Concept A high flow mode has been established for this study as 150% of the fresh (non-recirculated) air flow provided by the current air conditioning system when using the current passenger cabin smoke evacuation emergency procedure. This objective includes a proviso that no complex components other than the pack flow control valve are to be modified; that is, the high flow may be less than 150% if necessary to preclude costly changes to withstand conditions such as flow and temperature increases in the bleed air components, air cycle machines and pack heat exchangers, and pressure increases in the distribution system.

The dual outflow valve requirement for Concept A has been established for this study as allowing all of the functions of the current cabin pressure control system to be provided by either a forward or aft outflow valve while fully closing the valve(s) at the opposite end of the airplane. This requirement for a single outflow location is satisfied by two operating valves if they are adjacent to each other as in Boeing 727-100 airplanes. These outflow valve open/closed positions will be maintained after engine shutdown to assure that cabin pressure will not prevent door opening for passenger evacuation.

4.2.3 CONCEPT A: DESCRIPTIONS AND COST ESTIMATES

4.2.3.1 BOEING 707 CHANGES

4.2.3.1.1 High Flow Mode

A. Standard Airplanes:

The objective flow increase can be obtained by selecting the combination of air sources that will provide maximum distribution duct manifold pressure of 20 inches of water. This procedure requires 3 turbo compressors (T/C) and 4 engine bleed air sources and will provide about 4500 cfm total flow of which 4050 cfm will flow to the passenger cabin.

B. Airplanes With Two Turbo Compressors:

Airplanes with only 2 T/C's will be modified to install a third T/C on the No. 4 engine (See Figure 4.2.3.1-1).

Install wiring and controls for third T/C operation.

C. Airplanes Without Engine Bleeds: (Note: This modification is covered by 707 Service Bulletin 775 dated 3-10-60.)

Airplanes without an engine bleed air supply system will be modified to install ducting between the engine bleed port and the wing leading edge duct including a check valve and a shut-off valve. This is required on all four engines (See Figure 4.2.3.1-1).

Install wiring and controls for bleed air valve operation.

4.2.3.1.2 Dual Outflow Valve

A. Airplanes equipped with the Electro-Pneumatic Cabin Pressure Control System (see Figure 4.2.3.1-2) or the Pneumatic Cabin Pressure Control System using outflow valves with the electric override (see Figure 4.2.3.1-3) require no changes since controls exist for individual control of the outflow valves.

B. Airplanes equipped with the Pneumatic Cabin Pressure Control System without the electric override on the outflow valves:

Replace the forward and aft outflow valves with outflow valves with the electric override.

Install cockpit controls to operate the forward outflow valve and the solenoid operated valves.

Revise pneumatic control tubing to accommodate new valve.

Install solenoid operated shut-off valves in the pneumatic control lines to the valves.

Install wiring to provide power to forward outflow valve and solenoid valves and wiring from the valves to the cockpit.

The total cost (non-recurring and per-airplane) to incorporate these changes by retrofit of the current U.S. fleet of 36 airplanes is estimated to be about $1,900,000.

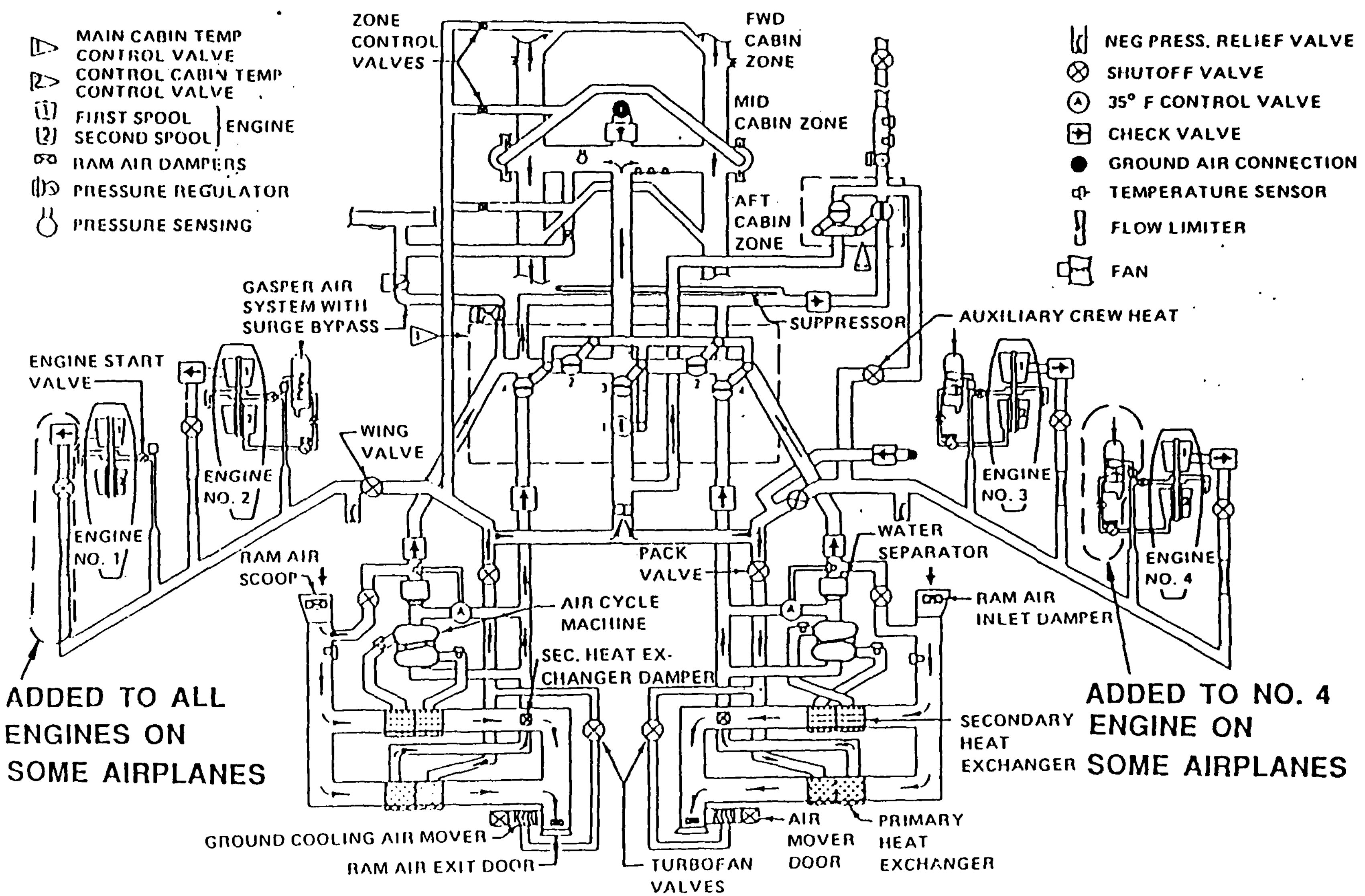


FIGURE 4.2.3.1-1. CONCEPT A, 707, HIGH FLOW MODE

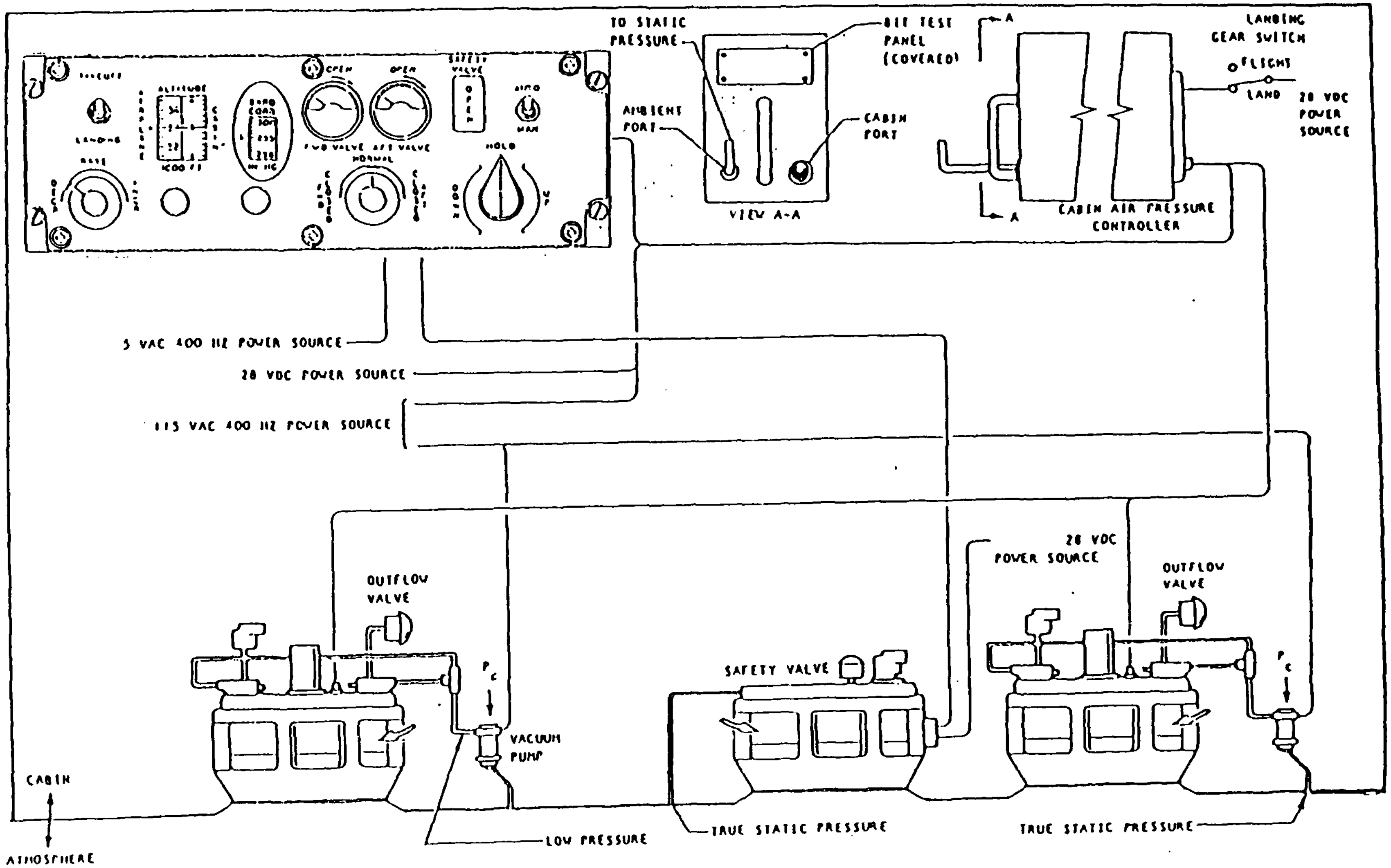


FIGURE 4.2.3.1-2. CONCEPT A, 707, DUAL OUTFLOW VALVE ELECTRO-PNEUMATIC

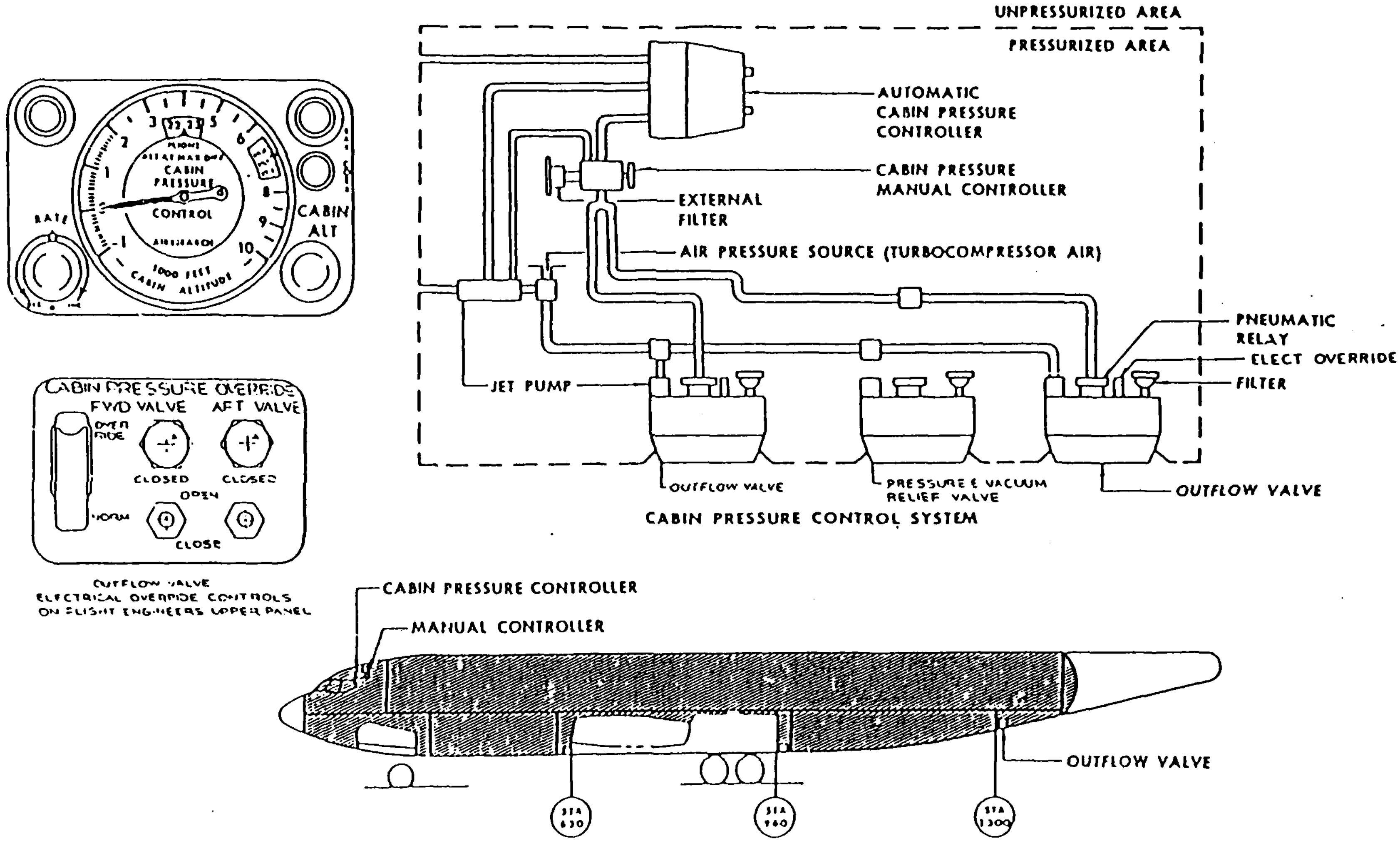


FIGURE 4.2.3.1-3. CONCEPT A, 707, DUAL OUTFLOW VALVE PNEUMATIC

4.2.3.2 BOEING 727-100 CHANGES

4.2.3.2.1 High Flow Mode

There is no margin for increasing the flow of the 727-100 packs without a major pack re-design (See Figure 4.2.3.2-1).

4.2.3.2.2 Dual Outflow Valve (See Figure 4.2.3.2-2)

Install a 707 type outflow valve with an electrical override in the area between the nose wheel well and the forward cargo compartment.

Provide a hole in the skin and install a pedestal for the addition of the outflow valve.

Install pneumatic control tubing for the controller and the fan venturi unit to the new outflow valve.

Install solenoid controlled shut-off valves in the pneumatic control lines.

Install controls in the cockpit for forward valve operation.

Install wiring for operation of the forward outflow valve including the solenoid operated valves.

The total cost (non-recurring and per-airplane) to incorporate these changes by retrofit of the current U.S. fleet of 344 airplanes is estimated to be about $9,900,000.

NO MODIFICATIONS FOR THIS CONCEPT

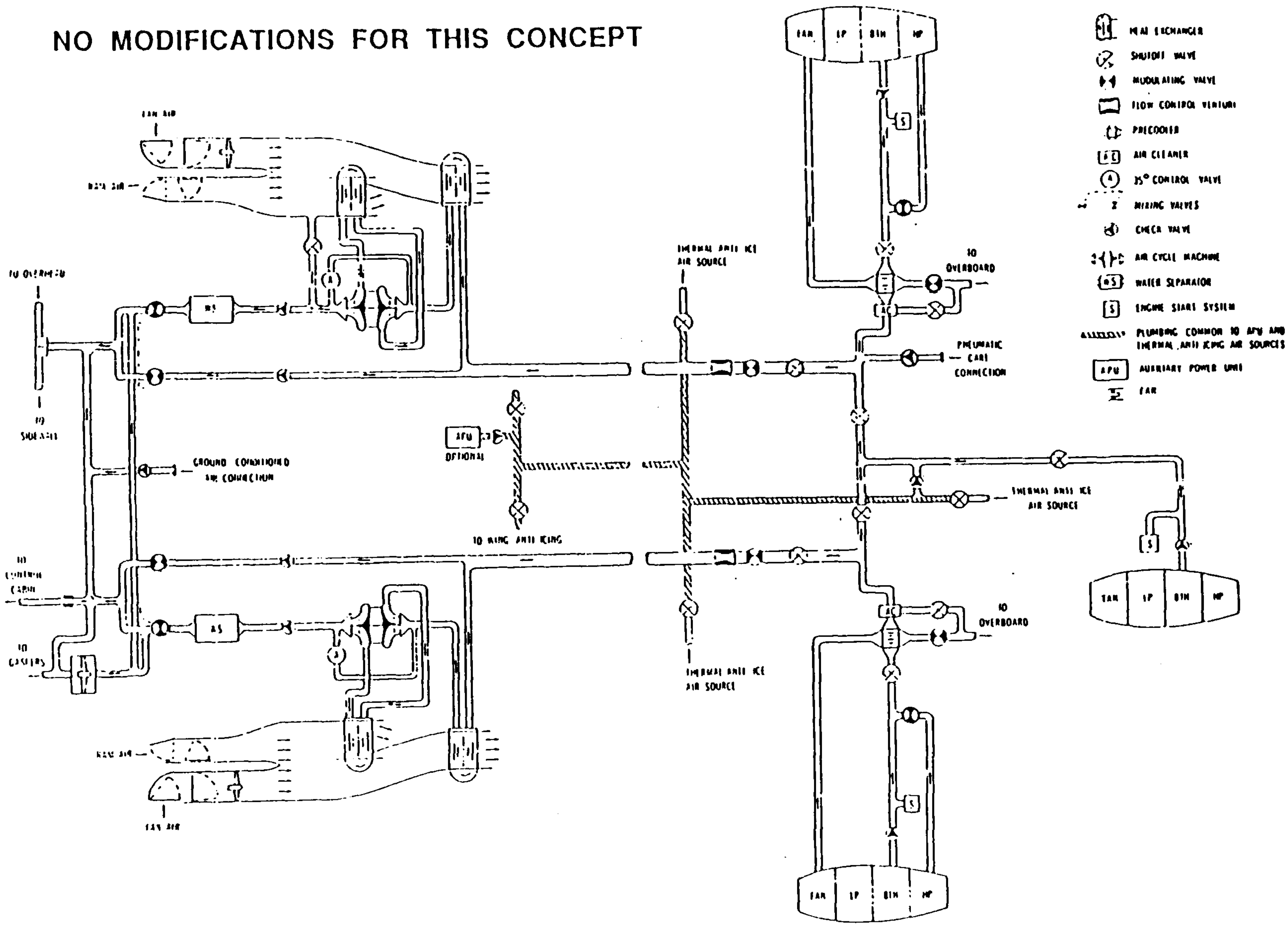


FIGURE 4.2.3.2-1. CONCEPT A, 727-100, HIGH FLOW MODE

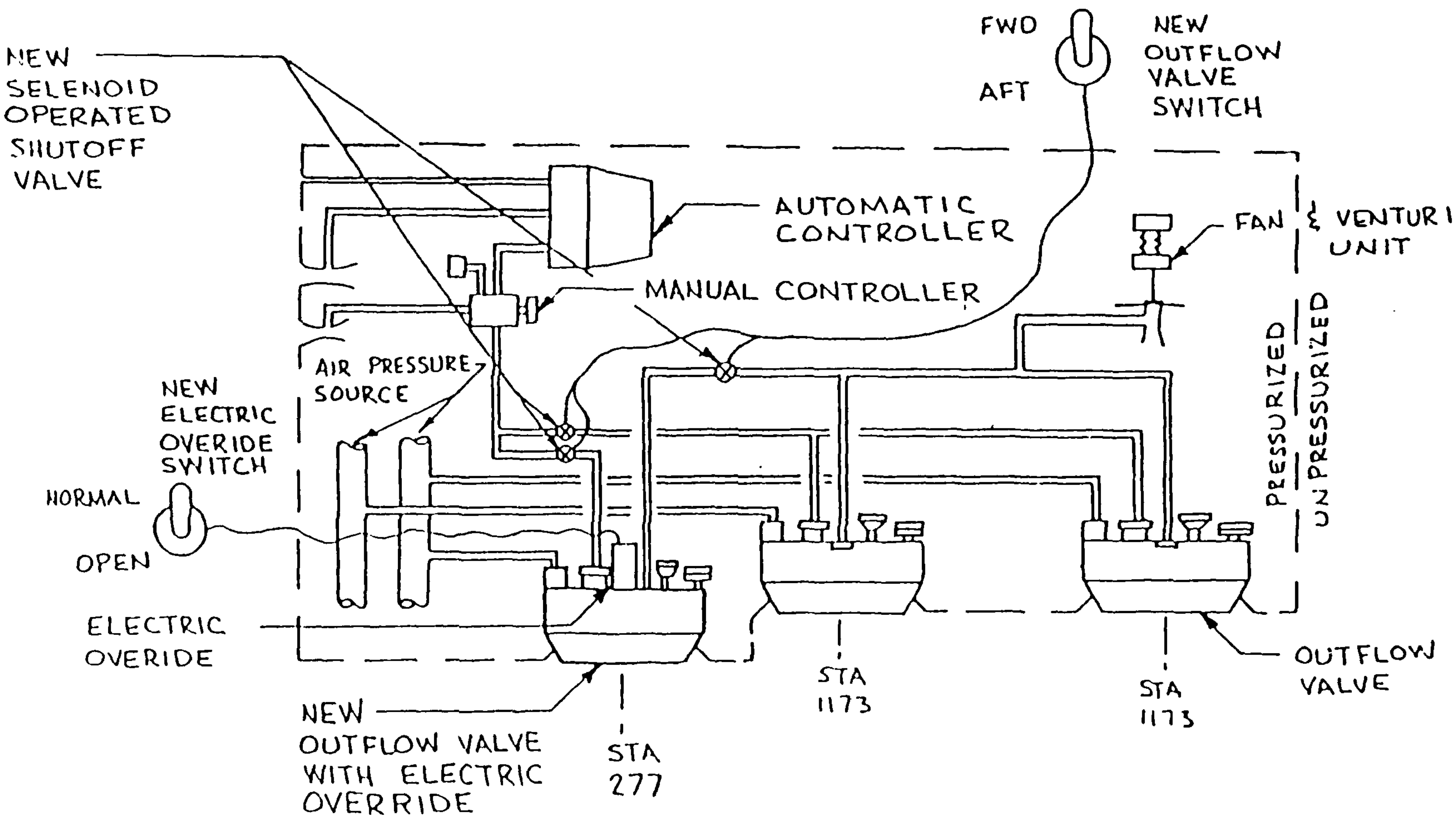


FIGURE 4.2.3.2-2 CONCEPT A, 727-100, DUAL OUTFLOW VALVE

4.2.3.3 BOEING 727-200 CHANGES

4.2.3.3.1 High Flow Mode

Modify L.H. and R.H. flow control valves to incorporate a high flow operating mode to provide 115% of the current flow capacity (See Figure 4.2.3.3-1).

Install the L.H. and R.H. flow control valves.

Add controls in the cockpit to select the high-flow mode.

Install wiring from cockpit to flow control valves.

4.2.3.3.2 Dual Outflow Valve.

A. Airplanes equipped with the Pneumatic Cabin Pressure Control System : This addition will be the same as the dual outflow valve per Paragraph 4.2.3.2.2.

B. Airplane equipped with the Electronic Cabin Pressure Control System (See Figure 4.2.3.3-2):

Install a second outflow valve identical to the existing valve in the area between the nose wheel and the forward cargo compartment.

Provide a hole in the skin and install mounting provision for the addition of the outflow valve.

Add controls in the cockpit select forward or aft valve operation.

Install wiring for the operation of the forward outflow valve including a relay.

The total cost (non-recurring and per-airplane) to incorporate these changes by retrofit of the current U.S. fleet of 853 airplanes is estimated to be about $26,200,000.

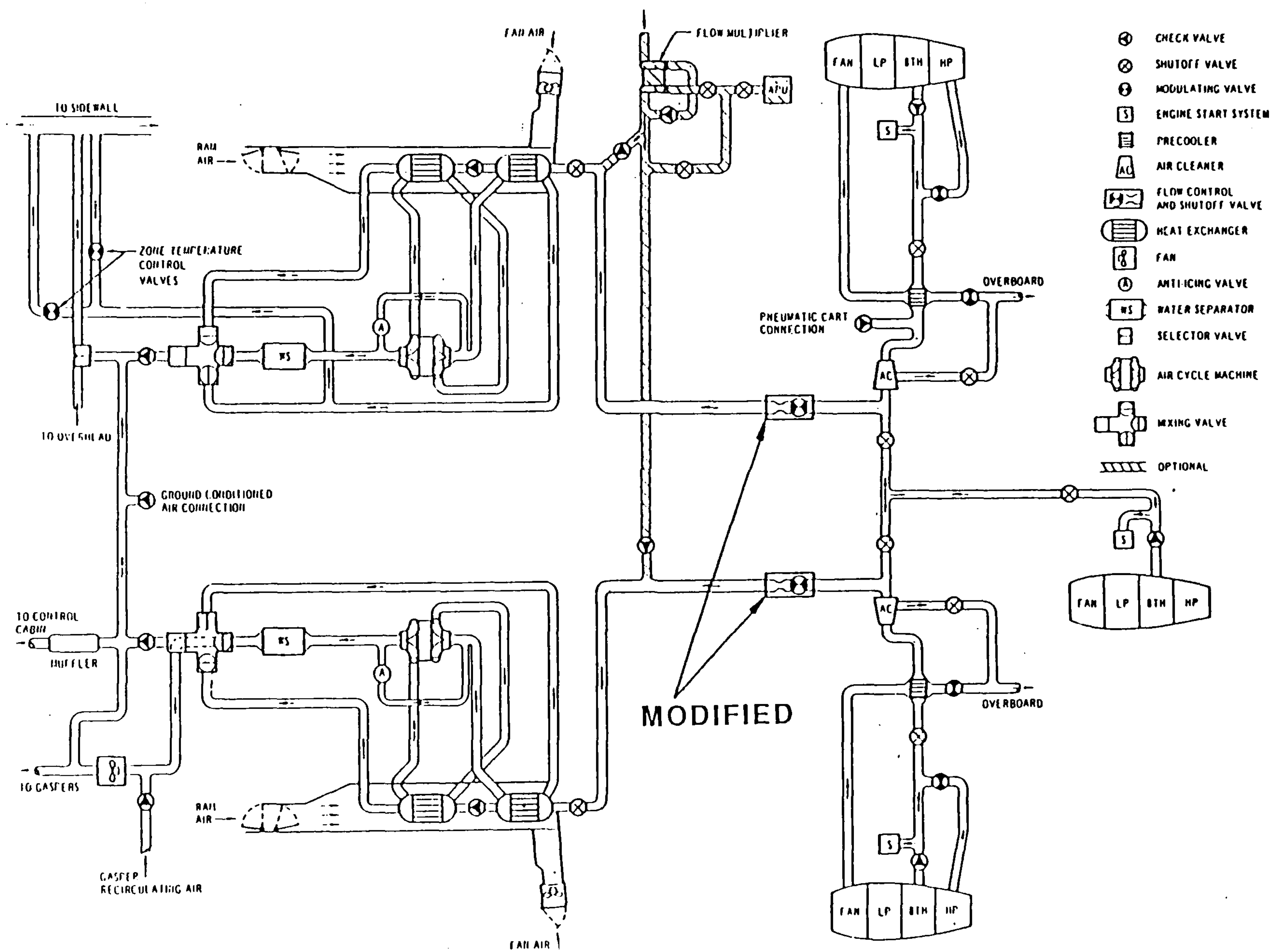


FIGURE 4.2.3.3-1 CONCEPT A 727-200 HIGH FLOW MODE

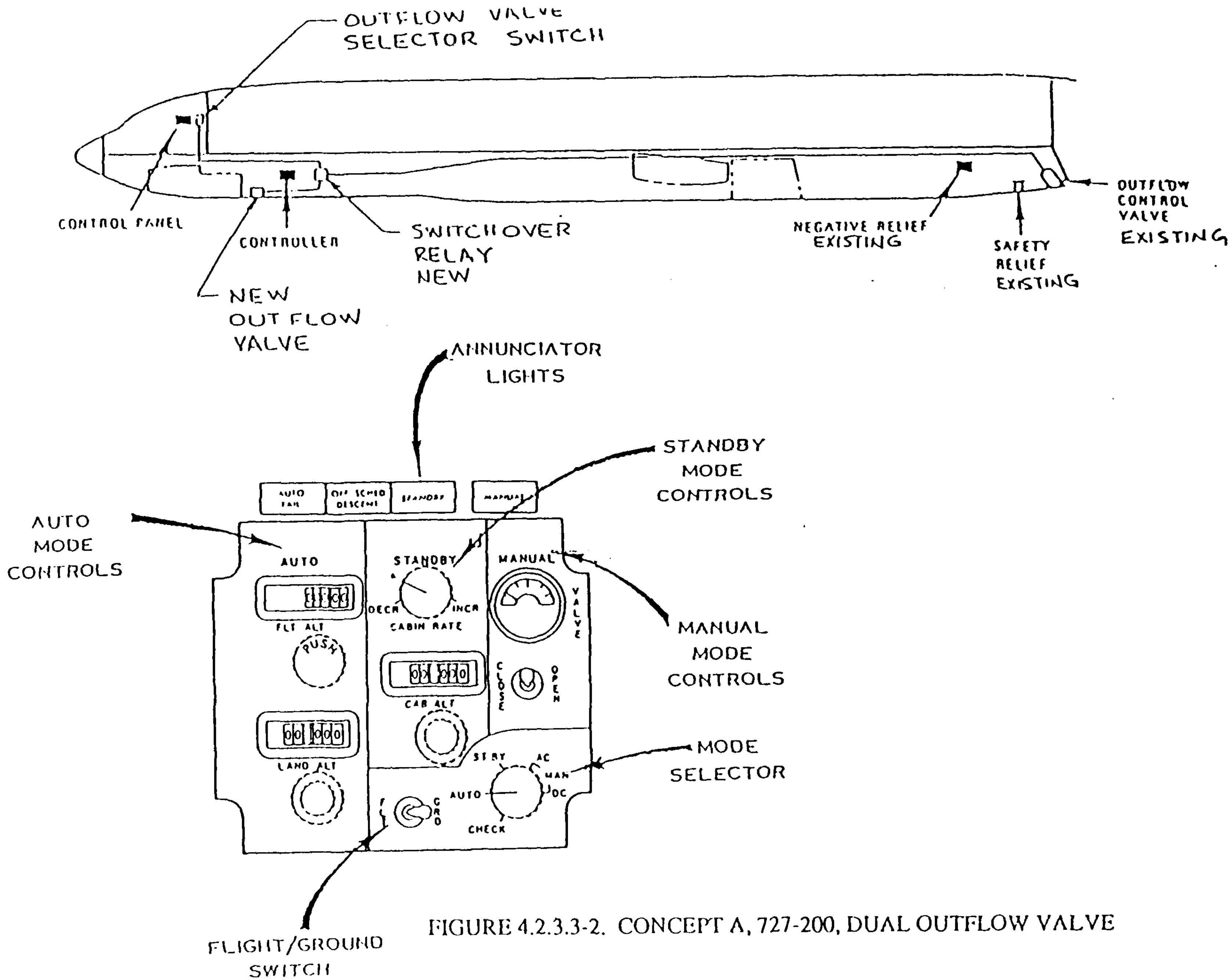


FIGURE 4.2.3.3-2. CONCEPT A, 727-200, DUAL OUTFLOW VALVE

4.2.3.4 BOEING 737 CHANGES

4.2.3.4.1 High Flow Mode

Both air conditioning pack flow control valves will be replaced with modified flow control valves with a high flow mode that will provide 150% of the ventilation provided by the current system during use of the passenger cabin smoke evacuation procedure (See Figures 4.2.3.4-1 and 4.2.3.4-2).

Pack control logic will be modified to support the high flow capability.

Cockpit controls will be added to select the high flow mode.

Electrical wiring will be added between the flow control valves and the cockpit.

4.2.3.4.2 Dual Outflow Valve

A twin of the current cabin pressure control outflow valve will be added in the forward lower fuselage, right hand side, in the vicinity of the E/E bay. This added outflow valve will provide the same cabin pressure control as the current valve.

The structure around the added valve will be modified to support the mounting flange of the added valve and maintain fuselage strength.

Cockpit controls will be added to select one valve to operate and to command the other valve to close.

Electrical wiring will be added between the added outflow valve and the cabin pressure controller (in E/E racks) and the cockpit.

The total cost (non [illegible] curring and per-airplane) to incorporate these changes by retrofit of the current U.S. fleet of 64 [illegible] planes is estimated to be about $17,700,000. For future production of 727 airplanes throug[illegible] 992. the cost is estimated to be about $20,200,000.

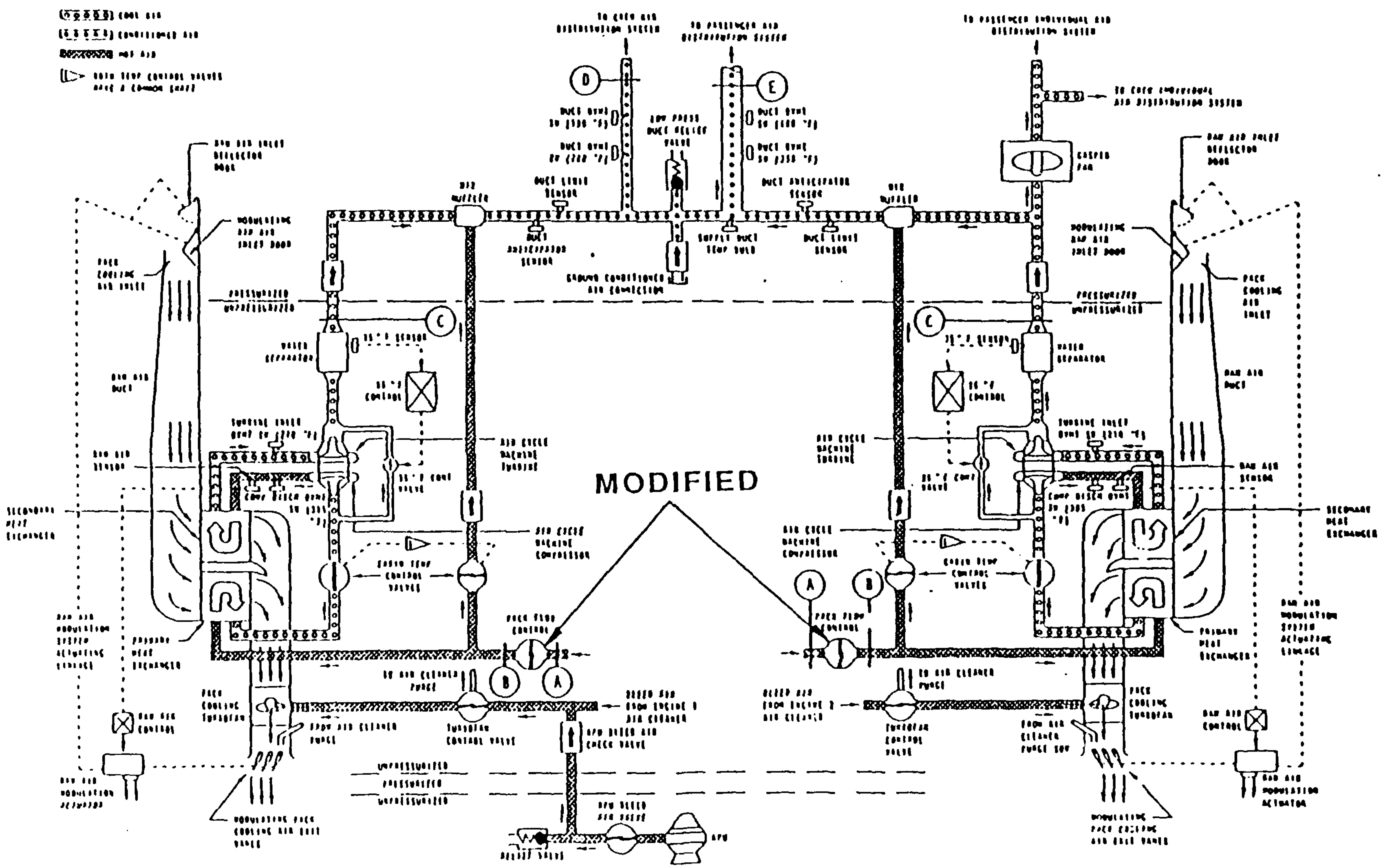


FIGURE 4.2.3.4-1 CONCEPT A, 737-100/200, HIGH FLOW MODE

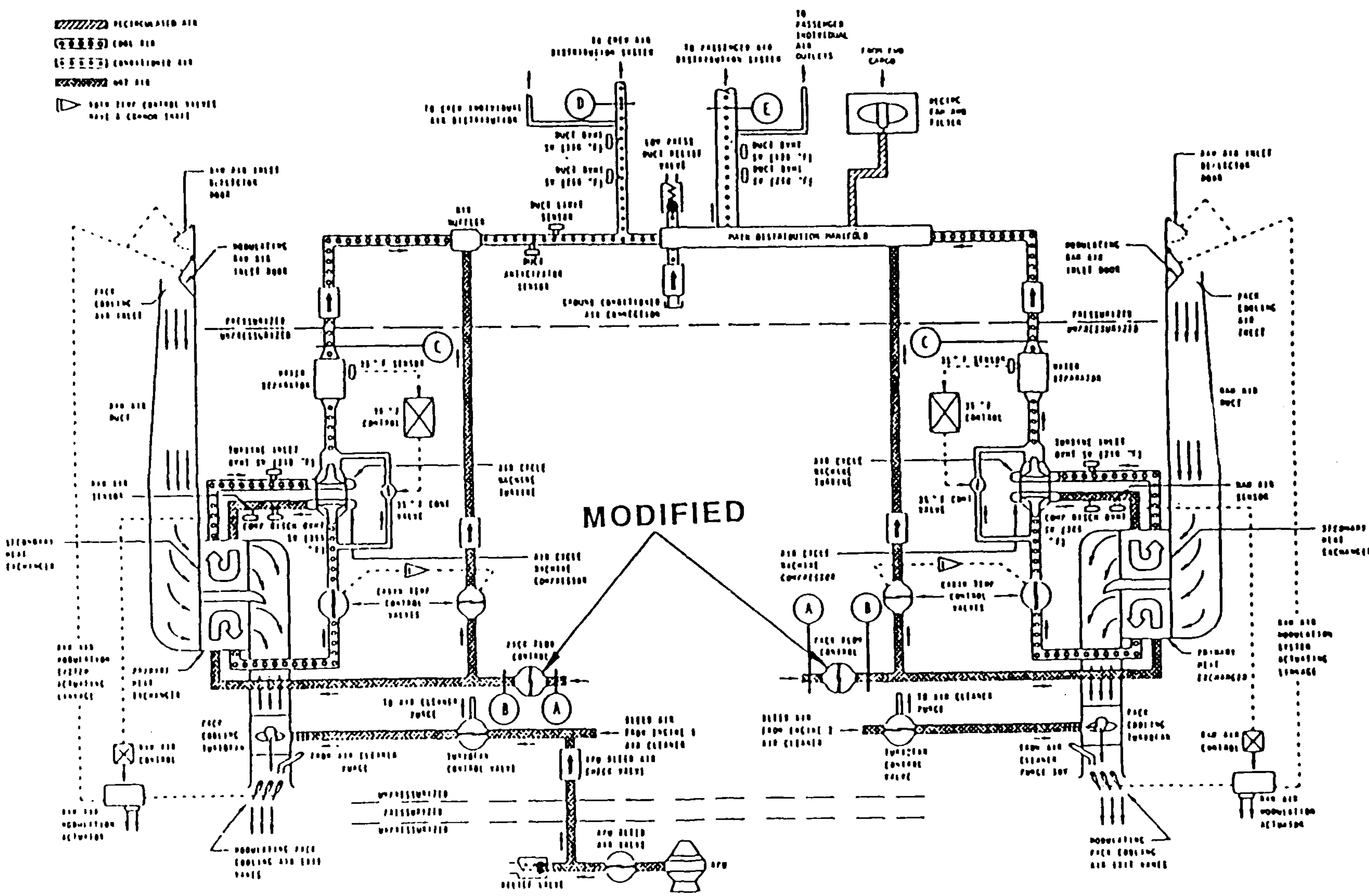


FIGURE 4.2.3.4-2. CONCEPT A, 737-300, HIGH FLOW MODE

4.2.3.5 BOEING 747 CHANGES

4.2.3.5.1 High Flow Mode

There is no margin for increasing the flow of the 747 packs without a major pack re-design (See Figure 4.2.3.5-1).

4.2.3.5.2 Dual Outflow Valve

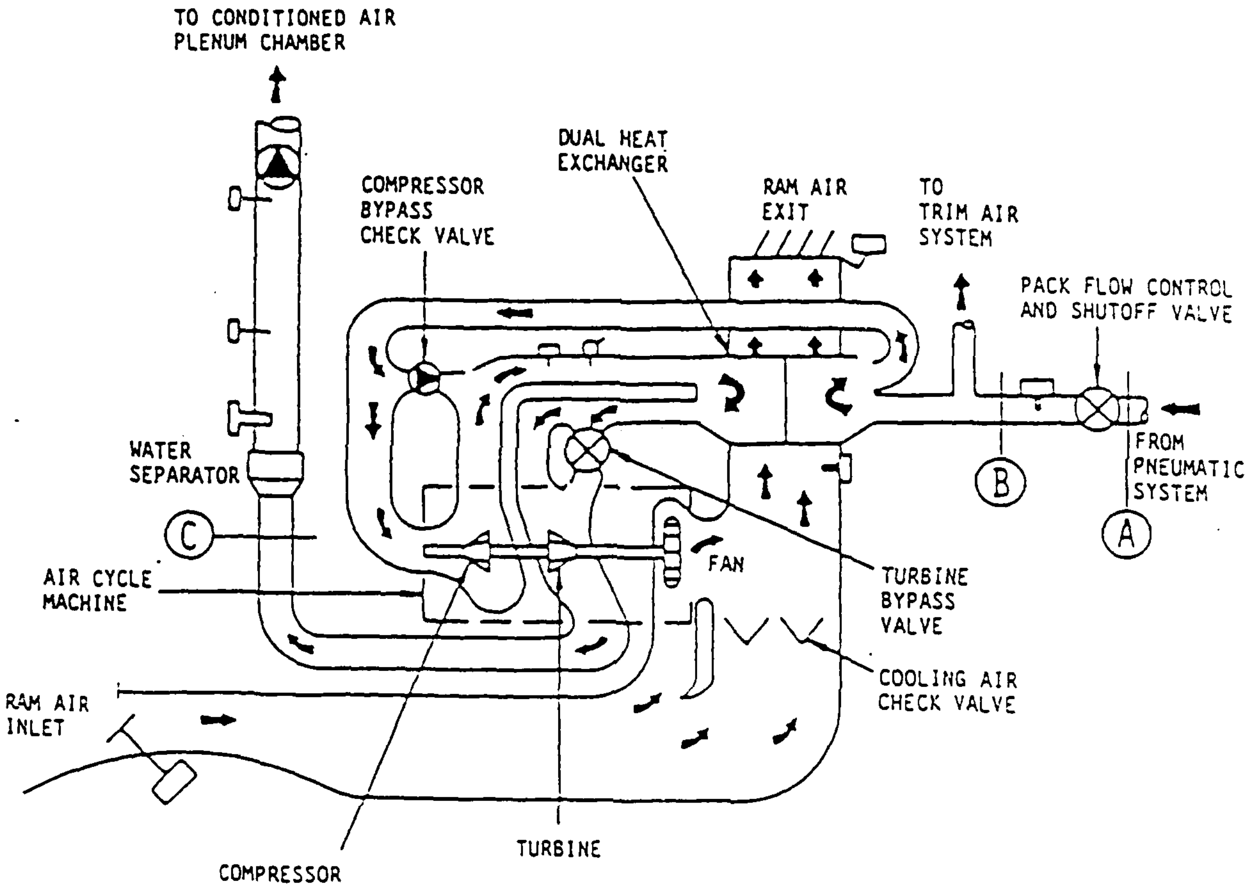
A single, current cabin pressure outflow valve will be installed below the floor of the forward cargo compartment. This added outflow valve will provide the same cabin pressure control as the current valves.

Cockpit controls will be added, along with provisions to the digital cabin pressure controller for the 747-400, to select the appropriate combinations of forward and aft valves to be operating. These combinations are described in Paragraph 4.2.1 except that when the smoke source is in the forward cabin (scenario 4) one forward and one aft valve will be used during approach and landing because the 747 needs 2 valves open to assure that cabin pressure will not prevent door opening.

Skin and frame structure around the new valve location will be modified to support valve and maintain fuselage strength.

Electrical wiring will be added between the outflow valve and the controller in the electrical equipment racks and the cockpit.

The total cost (non-recurring and per-airplane) to incorporate these changes by retrofit of the current U.S. fleet of 167 airplanes is estimated to be about $3,000,000. For future production of 226 airplanes through 1992, the cost is estimated to be about $5,100,000.



NO MODIFICATIONS FOR THIS CONCEPT

FIGURE 4.2.3.5-1. CONCEPT A, 747, HIGH FLOW MODE

4.2.3.6 BOEING 757 CHANGES

4.2.3.6.1 High Flow Mode

Both air conditioning pack flow control valves will be replaced with modified flow control valves with a high flow mode that will provide 130 percent of the flow provided by the current system during use of the passenger cabin smoke evacuation procedure (See Figure 4.2.3.6-1).

Pack control logic will be modified to support the high flow capability.

Cockpit controls will be added to select the high flow mode.

Electrical wiring will be added between the flow control valves and the cockpit.

4.2.3.6.2 Dual Outflow Valve

A twin of the current cabin pressure control outflow valve will be added in the forward lower fuselage, left hand side, in the vicinity of the E/E bay. This added outflow valve will provide the same cabin pressure control as the current valve.

The structure around the added valve will be modified to support the mounting flange of the added valve and maintain fuselage strength.

Cockpit controls will be added to select one valve to operate and to command the other valve to close.

Electrical wiring will be added between the added outflow valve and the cabin pressure controller (in E/E rack) and the cockpit.

The total cost (non-recurring and per-airplane) to incorporate these changes by retrofit of the current U.S. fleet of 98 airplanes is estimated to be about $3,200,000. For future production of 187 airplanes through 1992, the cost is estimated to be about $6,300,000.

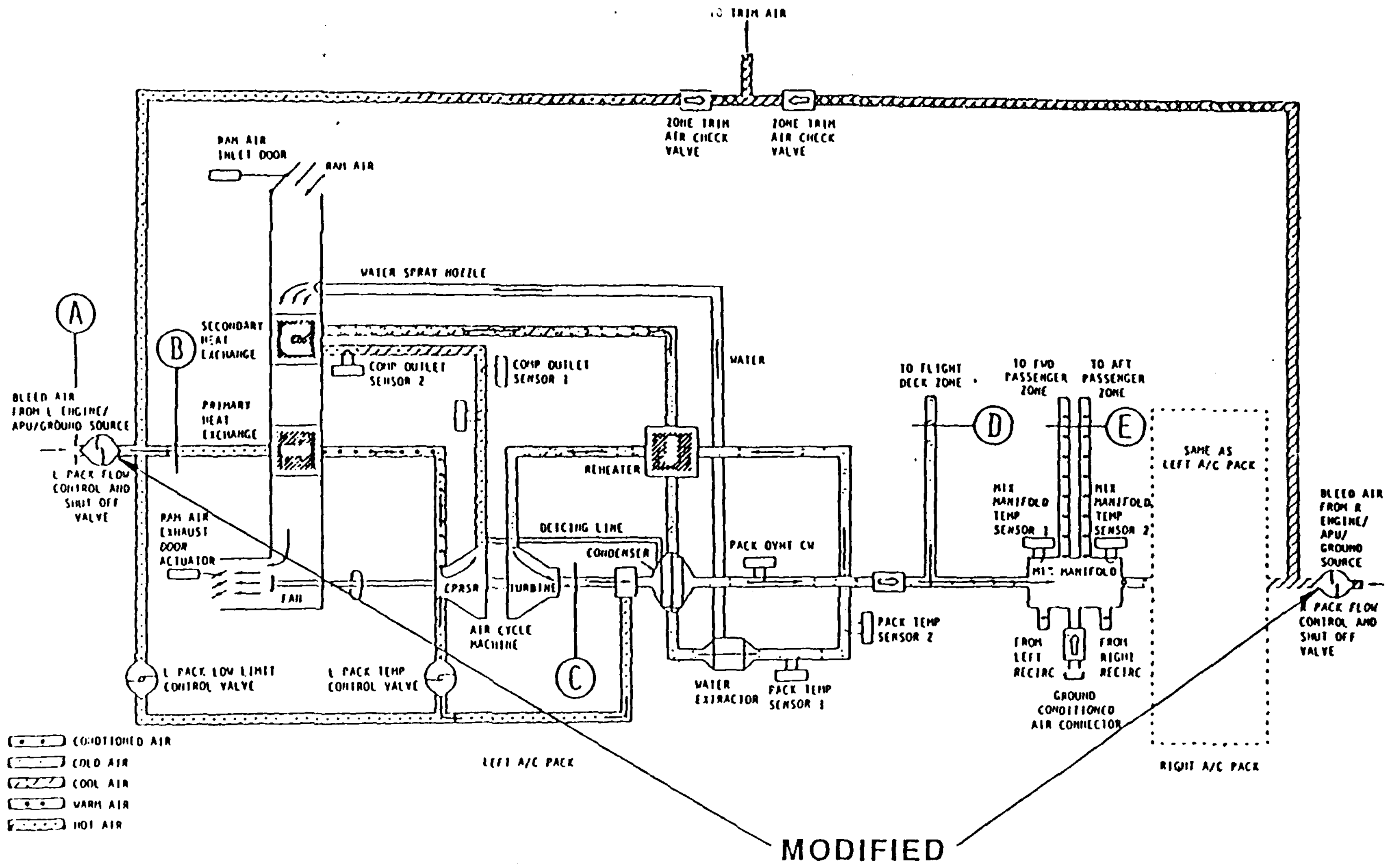


FIGURE 4.2.3.6-1. CONCEPT A, 757, HIGH FLOW MODE

4.2.3.7 BOEING 767 CHANGES

4.2.3.7.1 High Flow Mode

There is no margin for increasing the flow of the 767 packs without a major pack re-design (See Figure 4.2.3.7-1).

4.2.3.7.2 Dual Outflow Valve

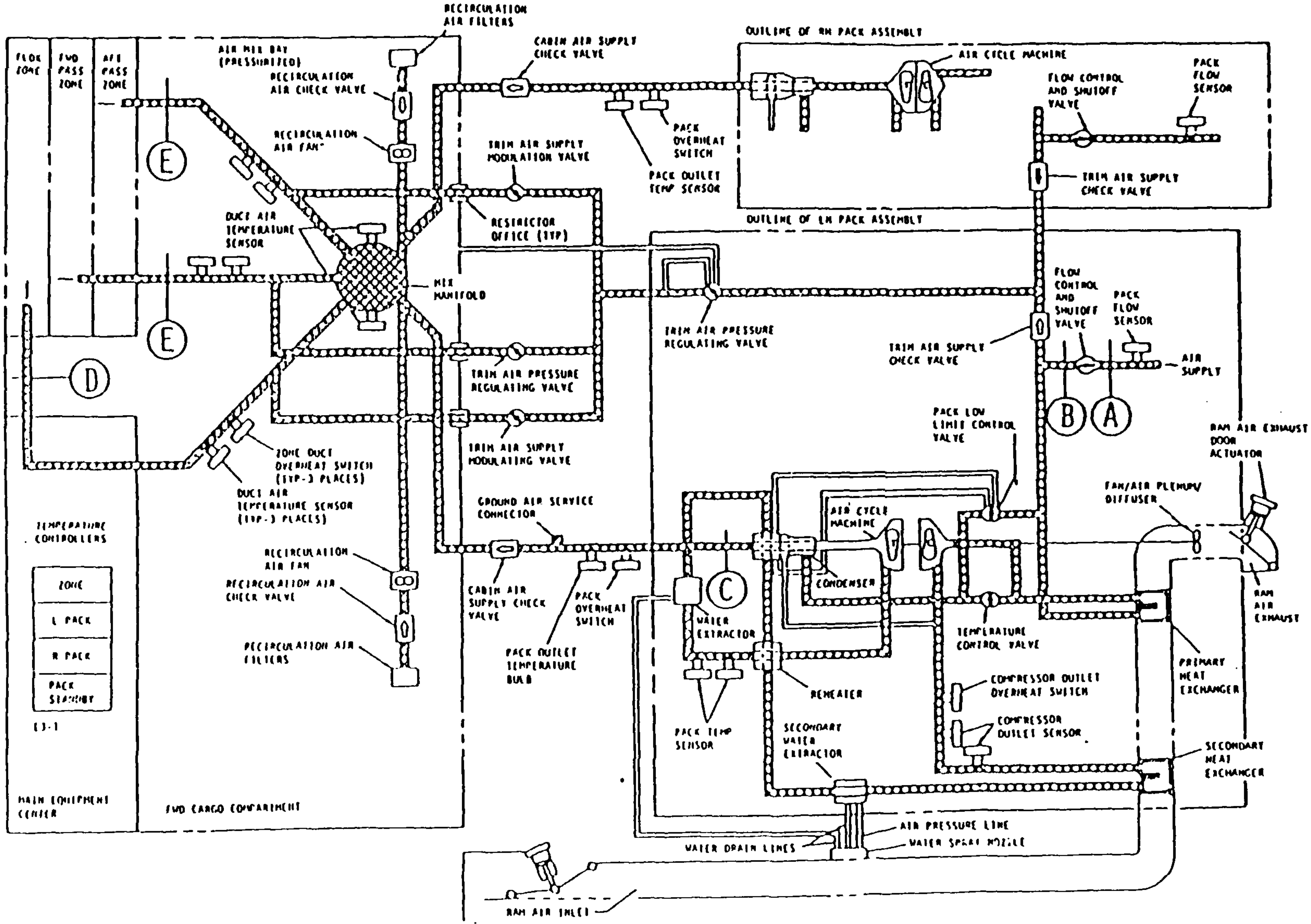
A twin of the current outflow valve will be installed below the floor of the forward cargo compartment. This valve will provide the same control of cabin pressure as the existing valve at the rear of the airplane.

The structure around the added valve will be modified to support the mounting flange and maintain fuselage strength.

Cockpit controls will be added to select one valve to operate and to command the other valve to close.

Electrical wiring will be added between the outflow valve and the cabin pressure controller in electrical equipment racks and the cockpit.

The total cost (non-recurring and per-airplane) to incorporate these changes by retrofit of the current U.S. fleet of 87 airplanes is estimated to be about $1,700,000. For future production of 212 airplanes through 1992, the cost is estimated to be about $4,400,000.



NO MODIFICATIONS FOR THIS CONCEPT

FIGURE 4.2.3.7-1. CONCEPT A, 767, HIGH FLOW MODE

4.2.3.8 DOUGLAS DC-8

4.2.3.8.1 GENERAL

Air conditioning and pressurization is provided by two identical air conditioning packs which are designed for independent or parallel operation. Original DC-8 airplanes have two pack vapor-cycle (Freon) air conditioning packs that use auxiliary compressors as an air source. The DC- 8-70 series airplanes use direct engine compressor bleed air through an air- cycle air conditioning system (see Figure 4.2.3.8-1). For this study only the DC-8- 70 series will be addressed. On the -70 series airplanes, the air conditioning packs are located below the flight deck on either side of the aircraft centerline in the unpressurized areas on both sides of the nose wheel well. The right-hand system supplies air to the cabin only and the left system is interconnected to supply air to the cockpit and the passenger cabin.

Pressure within the cabin is maintained by controlling the amount of air exhausted from the cabin through the cabin air outflow valve which is located on the underside of the fuselage, aft of the aft cargo compartment. The valve consists of a butterfly valve and a nozzle valve interconnected by a drive assembly. The system can be controlled automatically or manually from the cockpit.

4.2.3.8.2 CHANGES

4.2.3.8.2.1 High Flow Mode

Both air conditioning pack flow control valves will be replaced with modified flow control valves with a high flow mode that will provide approximately 125% of the flow provided by the current system when the passenger cabin smoke evacuation procedure is being used (see Figure 4.2.3.8-1).

Cockpit controls will be added to select the high-flow mode.

Electrical wiring will be added to select the high-flow mode.

4.2.3.8.2.2 Dual Outflow Valve

To provide the same cabin pressure control as the current valve, a twin of the current cabin pressure control outflow valve will be added in the fuselage, aft of the forward cargo compartment (see Figure 4.2.3.8-2).

The structure around the added valve will be modified to support the mounting flange of the added valve and maintain fuselage strength.

Cockpit controls will be added to select one valve to operate and to command the other valve to close.

Electrical wiring will be added between the outflow valves, the cabin pressure controller (located in the electrical equipment racks), and the cockpit instrument panel.

The total cost (non-recurring and per-airplane) to incorporate these changes by retrofit of the current U.S. fleet of 188 airplanes is estimated to be about $22,700,000.

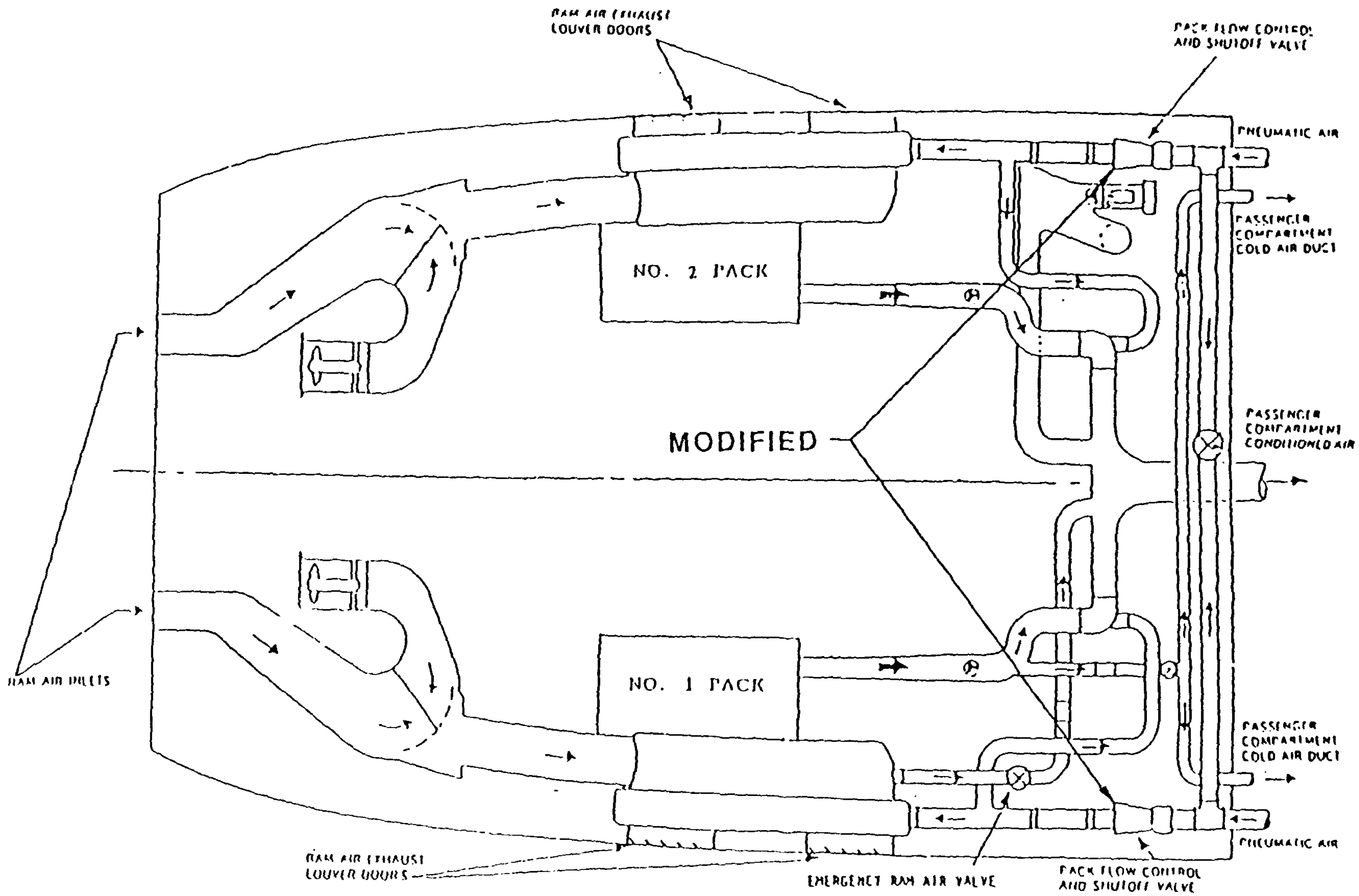


FIGURE 4.2.3.8-1. CONCEPT A, DC-8, HIGH FLOW MODE

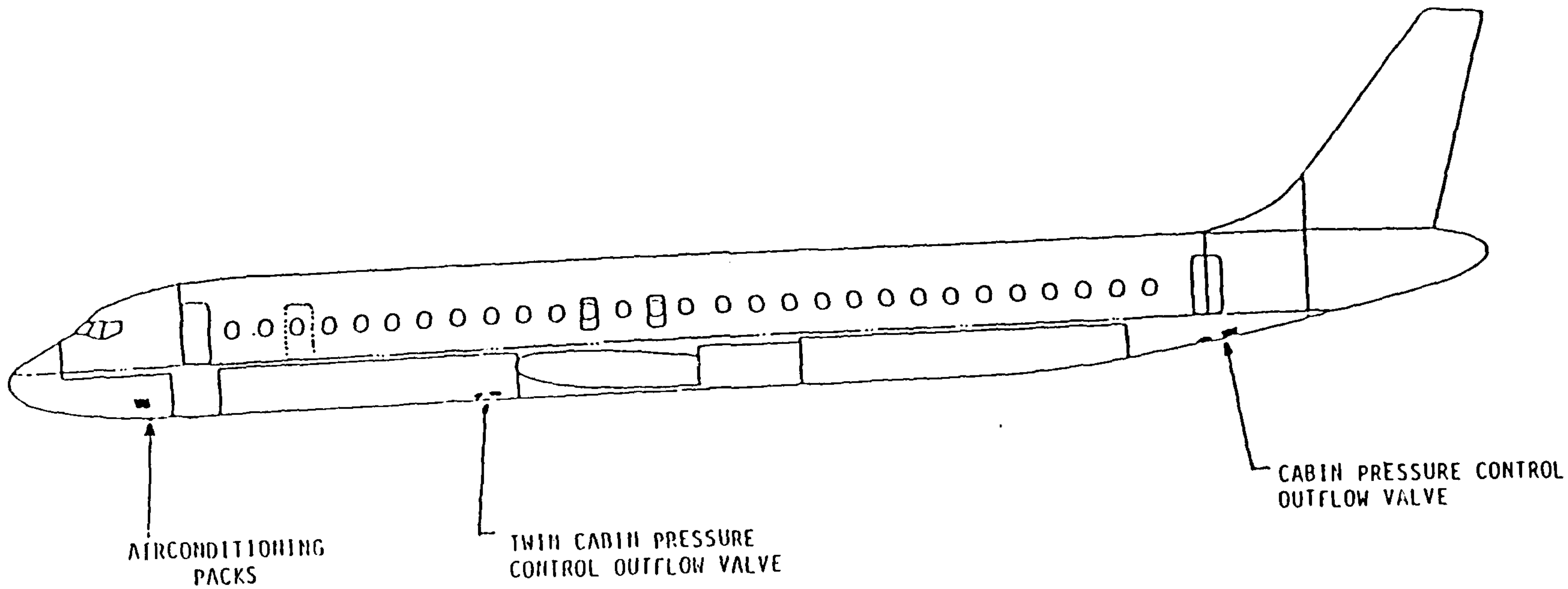


FIGURE 4.2.3.8-2. CONCEPT A, DC-8, DUAL OUTFLOW VALVE

4.2.3.9 DOUGLAS DC-9/MD-80

4.2.3.9.1 GENERAL

Airplane pressurization and air conditioning is provided by two identical air conditioning and pressurization systems which are designed for independent or parallel operation (see Figure 4.2.3.9-1). Normally, the right-hand system operates from right engine bleed air and supplies the passenger compartment requirements. The left hand system operates from left engine bleed air and supplies the flight compartments plus a portion to the passenger compartment. Either system can supply the requirements of both compartments. Engine bleed air is supplied to the packs through the bleed air system manifold and flow control valves. Bleed air is obtained from the engine compressor at either the 8th stage or 13th stage. The flow control valves located at the packs control the flow of air to the packs at all times that the system bleed air pressure is high enough to satisfy the flow requirements.

Desired pressurization level is maintained by controlling the amount of air exhausted through the cabin outflow valve. The cabin air outflow valve is located at the left-hand side of the lower fuselage inboard of the nacelle. The outflow valve contains two controllable areas, a large butterfly valve and a variable area nozzle. The two portions of the outflow valve are controlled in sequence by a linkage that is operated either electrically by the outflow valve actuator during automatic cabin pressure control, or manually by a cable system during manual cabin pressure control.

4.2.3.9.2 CHANGES

4.2.3.9.2.1 High Flow Mode

Both air conditioning pack flow control valves will be modified to operate with a high flow mode that will provide approximately 106% of the flow provided by the current system when of the passenger cabin smoke evacuation procedure is being used (see Figure 4.2.3.9-1).

Cockpit controls will be added to select the high-flow mode.

Electrical wiring will be added to select the high-flow mode.

4.2.3.9.2.2 Dual Outflow Valve

To provide the same cabin pressure as the current valve, a twin of the current cabin pressure control outflow valve will be added in the left-hand side of the fuselage near the front end of the forward cargo compartment (see Figure 4.2.3.9-2).

The structure around the added valve will be modified to support the mounting flange of the added valve and maintain fuselage strength.

Cockpit controls will be added to select one valve to operate and to command the other valve to close.

Electrical wiring will be added to connect the outflow valves, the cabin pressure controller (located in the electrical equipment racks), and the cockpit instrument panel.

The total cost (non-recurring and per-airplane) to incorporate these changes by retrofit of the current U.S. fleet of 699 airplanes is estimated to be about $104,800,000. For future production of 502 airplanes through 1992, the cost is estimated to be about $ 60,900,000.

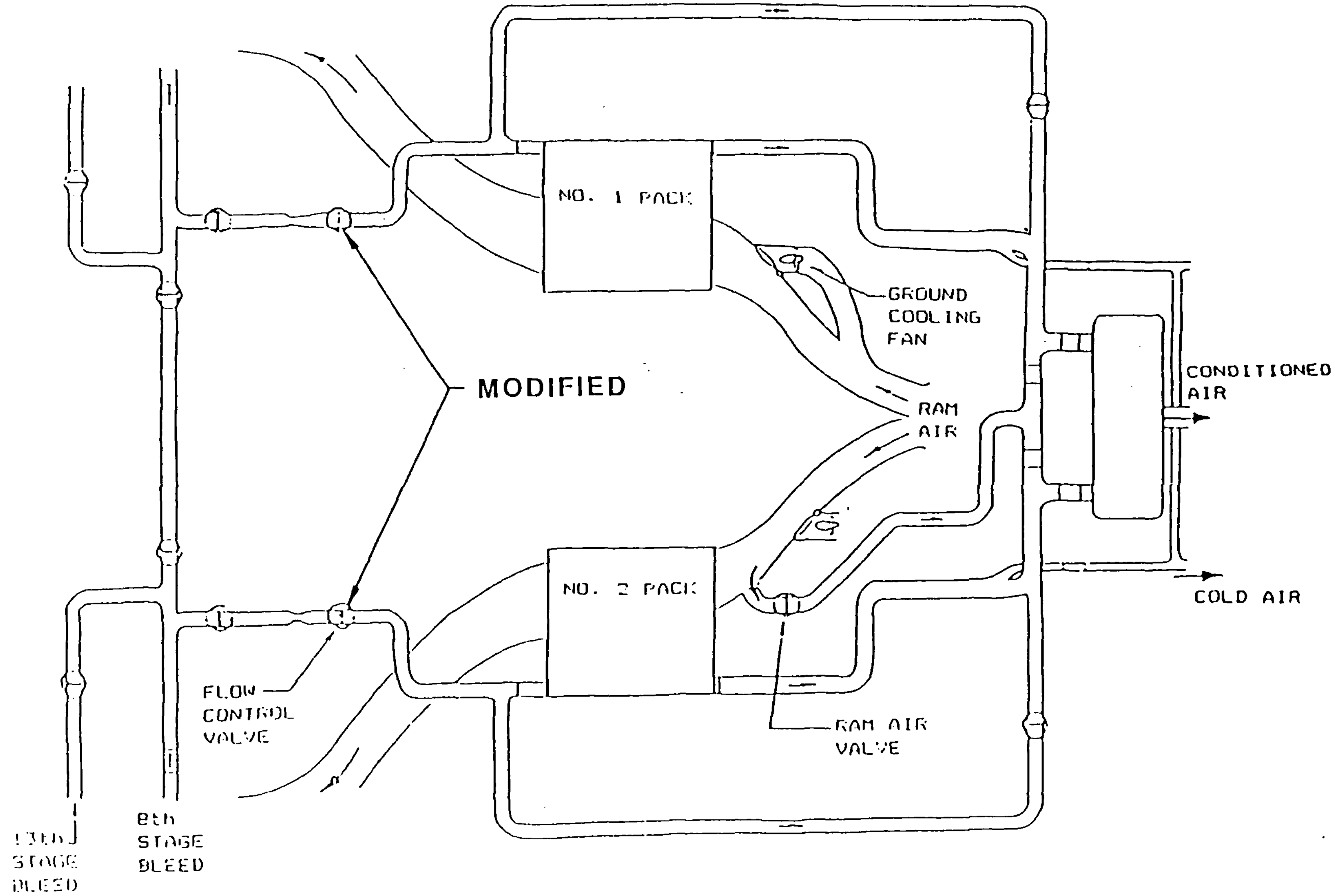


FIGURE 4.2.3.9-1. CONCEPT A, DC-9, HIGH FLOW MODE

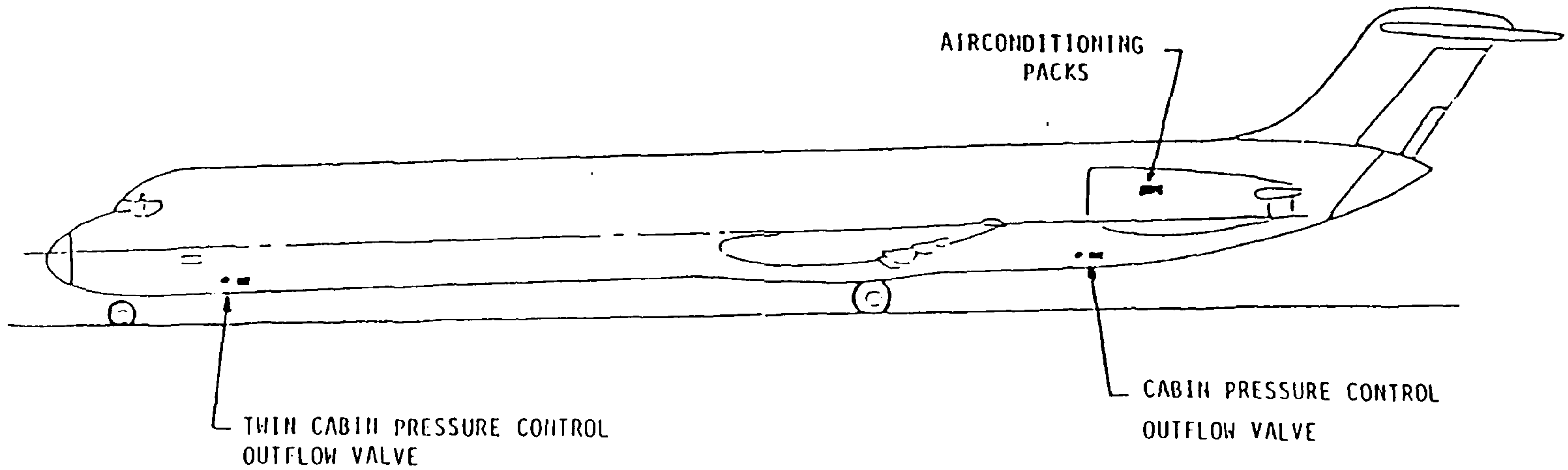


FIGURE 4.2.3.9-2. CONCEPT A, DC-9, DUAL FLOW VALVE

4.2.3.10 DOUGLAS DC-10

4.2.3.10.1 GENERAL

Air conditioning and pressurization is provided by three identical air conditioning packs (air cycle refrigeration machines), designed for independent or parallel operation (see Figure 4.2.3.10-1). Hot air from the bleed air system distribution manifold is supplied to each of the three refrigeration packs where it is cooled and then distributed to four or five aircraft zones for cooling, ventilating, and pressurization. The zones consist of the flight compartment, forward, mid and aft cabin area, and lower galley if installed. All of the air for the cockpit and lower galley is supplied by pack No. 1. The remaining airflow from pack No. 1, plus the air from pack No. 2 and No. 3, is delivered to the 3 passenger cabin zones. Engine bleed air is supplied to each of the three air conditioning packs through the bleed air distribution manifold and the flow control valves. Air is taken from each of the three engines at either the 8th of the 16th stages of the compressor. The flow control valves, located at the inlets to the packs, control the airflow to a predetermined schedule.

Desired pressurization level is maintained by regulating the outflow of conditioned air from the pressurized section of the airplane through the cabin pressure outflow valve. The outflow valve assembly is located on the left-hand side of the fuselage just forward of the wing. The assembly consists of a thrust recovery valve, a butterfly valve and a ram shield. The outflow valve is driven by either of two identical interchangeable actuators, one actuator being operated by the primary control system, and one by the standby control system. The three portions of the outflow valve are controlled in sequence so that the ram shield closes, then the butterfly, and the thrust recovery valve is closed last.

4.2.3.10.2 CHANGES

4.2.3.10.2.1 High-Flow Mode

All three air conditioning pack flow control valves will be replaced with modified flow control valves with a high flow mode that will provide approximately 115% of the flow provided by the current system when the passenger cabin smoke evacuation procedure is being used (see Figure 4.2.3.10-1).

Cockpit controls will be added to select the high-flow mode.

Electrical wiring will be added to select the high-flow modes.

4.2.3.10.2.2 Dual Outflow Valve

To provide the same cabin pressure control as the current valve, a twin of the current pressure control outflow valve will be added approximately on the left-hand side of the fuselage in the aft end of the aft cargo compartment (see Figure 4.2.3.10-2).

The structure around the added valve will be modified to support the mounting flange of the added valve and maintain fuselage strength.

Cockpit controls will be added to select one valve to operate and to command the other valve to close.

Electrical wiring will be added to connect the outflow valves, the cabin pressure controller (located in the electrical equipment racks), and the cockpit instrument panel.

The total cost (non-recurring and per-airplane) to incorporate these changes by retrofit of the current U.S. fleet of 190 airplanes is estimated to be about $34,500,000. For future production of 200 airplanes of derivative models through 1992, the cost is estimated to be about $ 35,200,000.

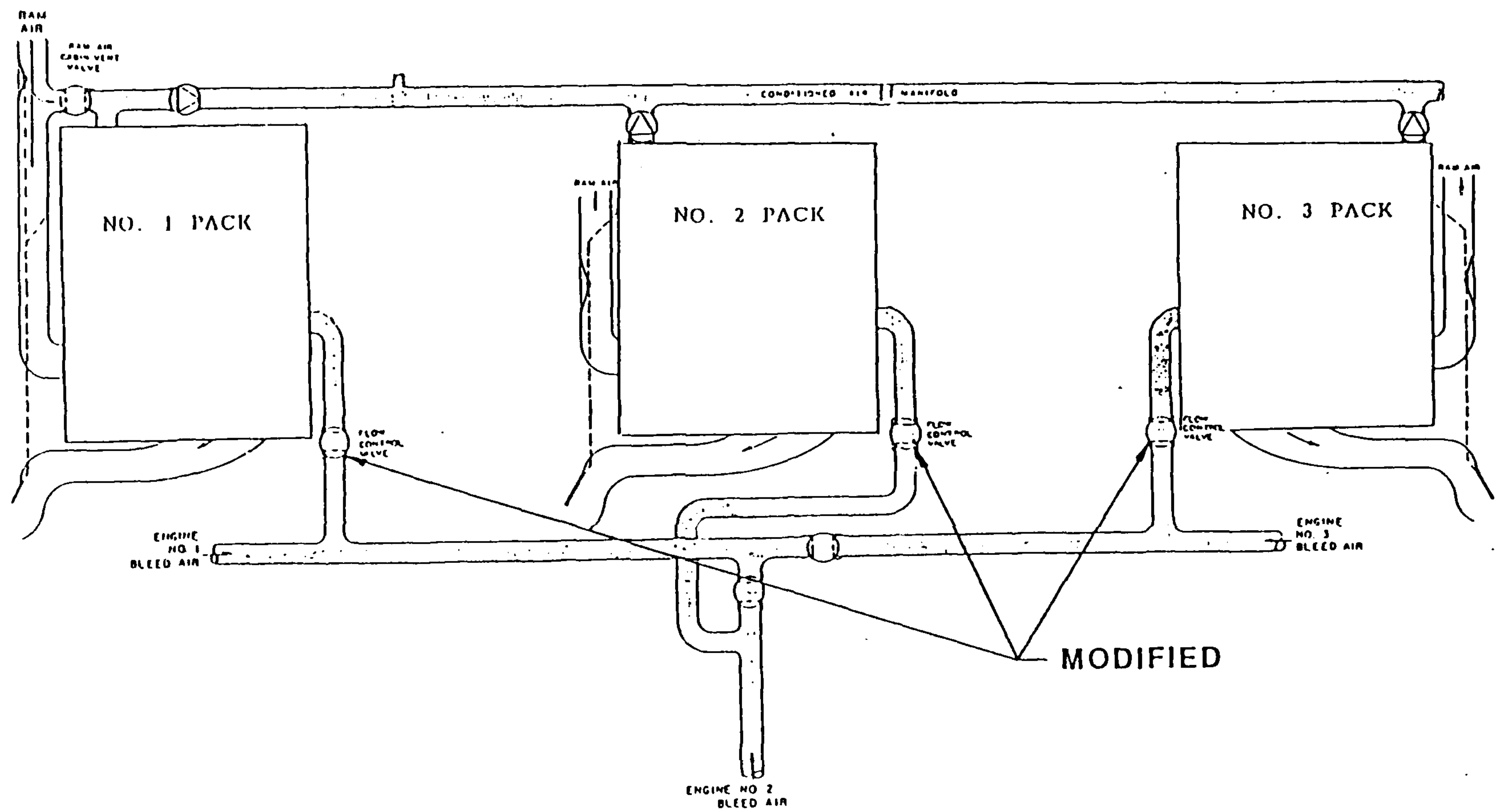


FIGURE 4.2.3.10-1. CONCEPT A, DC-10, HIGH FLOW MODE

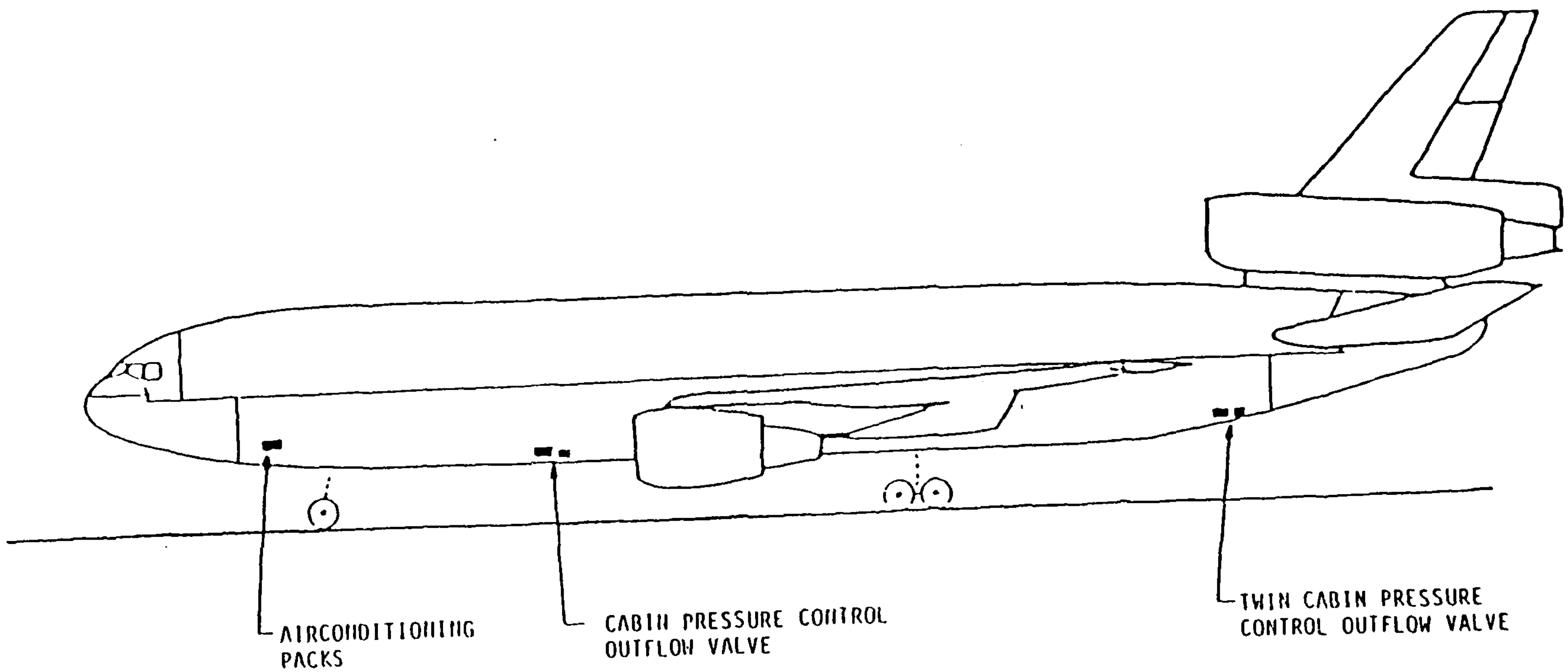


FIGURE 4.2.3.10-2. CONCEPT A, DC-10, DUAL OUTFLOW VALVE

4.3 CONCEPT B: RAM VENTILATION WITH ADDED DUMP VALVE

4.3.1 OUTLINE FROM PROPOSAL

Concept B (see Figure 4.3.1-1) provides for enhanced smoke venting during the passenger evacuation time period and provides for directional control of passenger smoke evacuation. This concept involves adding ram air ventilation with a battery powered fan and an overboard dump valve at the opposite end of the airplane from the current outflow valve. It will be operable from the time that the cabin is depressurized until the passengers are evacuated after landing and stopping the engines.

The operation of concept B is shown for a hypothetical case on Figure 4.3.1-1. The figure shows an inextinguishable smoke source assumed to be located in the aft passenger cabin and generating smoke at a rate such that the normal air conditioning cannot prevent the smoke cloud spreading into a large fraction of the passenger cabin. As shown on the altitude vs time profile the enhanced smoke operation is started after the airplane has descended and the cabin is depressurized. At the time labeled "Cabin Depressurized" the crew initiates the enhanced smoke operation by (1) stopping the air conditioning packs, (2) opening the ram ventilation valve and (3) opening the outflow valve. The ram ventilation will provide increased smoke-free air for the passengers to breathe and also create high, aft-directed axial flow velocity in the passenger cabin to push the smoke cloud toward the source and away from the passengers. If the smoke source is in the forward half of the cabin, the forward dump valve would be used to push smoke in the opposite direction by creating forward-directed axial flow. By turning on the battery powered fan when the airplane is slowing to a stop, the enhanced smoke venting will continue to operate after the engines are stopped. This means that smoke- free ventilation is provided during the passenger evacuation period that ends at the time labeled "Passengers Evacuated" on the figure.

4.3.2 CONCEPT B: REQUIREMENTS AND OBJECTIVES

The flow objective for Concept B ram ventilation has been established for this study as 150% of the fresh (non-recirculated) air flow provided by the current air conditioning system when using the current passenger cabin smoke evacuation emergency procedure. This ram and battery powered fan ventilation is desired to be maintained while the airplane is landing and stopping and continue for at least two (2) minutes after engine shutdown. This objective includes a proviso that no complex components other than the ram air system are to be modified; that is, the ram ventilation may be less than 150% if necessary to preclude costly changes to other components such as the distribution system ducts. Those airplanes that do not meet the 150% objective will use a combination of the air conditioning packs and/or ram ventilation to provide maximum airflow between the time of cabin depressurization and engine shutdown. In general, the ram ventilation fan(s) will be powered from the battery with the generator charging the battery until the engines are shutdown.

The added dump valve requirement for Concept B has been established for this study as allowing all of the cabin ventilation flow to be exhausted through either a forward or aft location after the airplane is depressurized. In airplanes with cabin pressure control systems having a single outflow valve or dual valves at adjacent locations, a new dump valve is required at the opposite end of the airplane from the current valve(s). In airplanes with at least one outflow valve at each end of the fuselage, the requirement can be satisfied by opening one valve while fully closing the other valve or valves in the system.

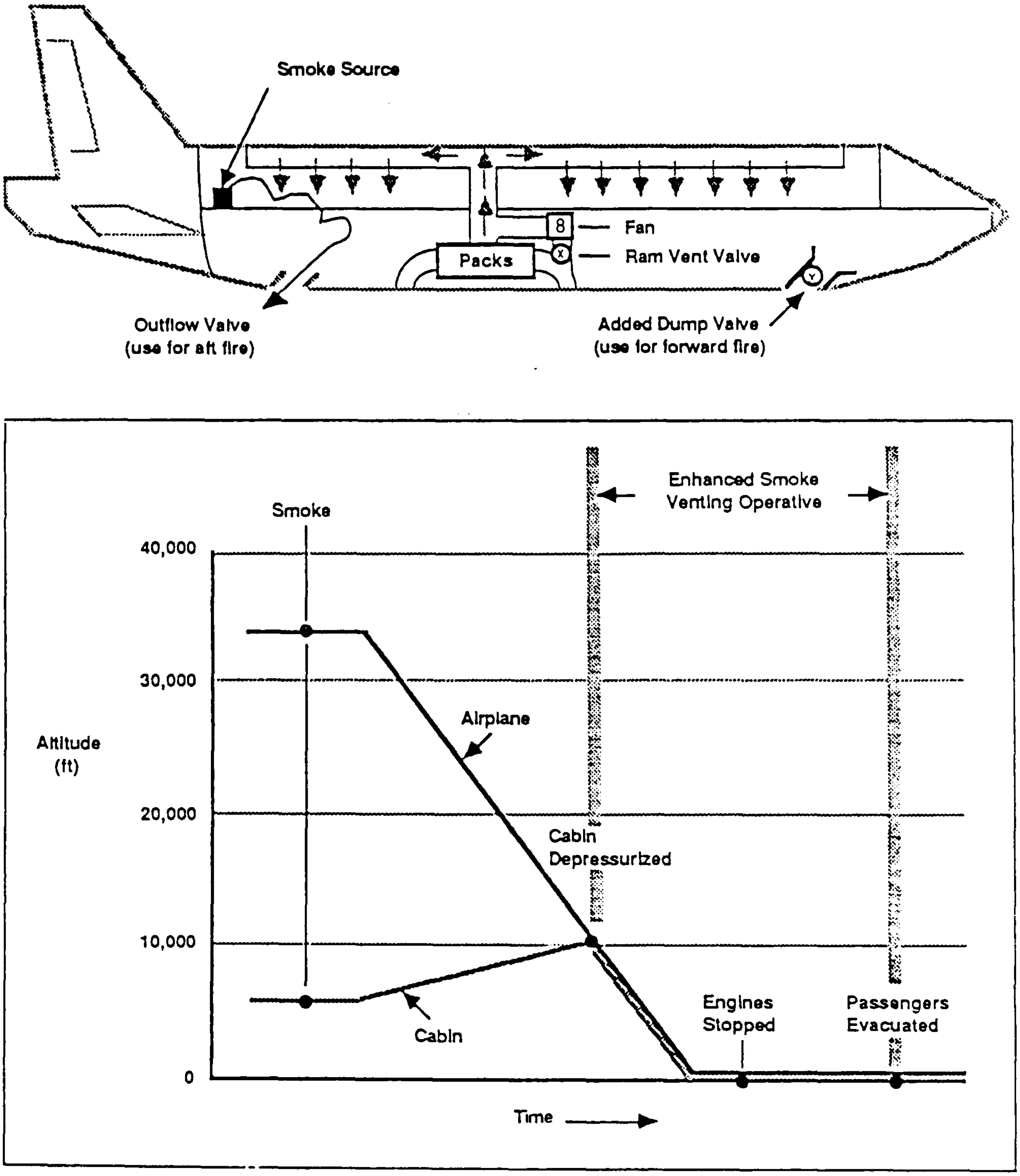


FIGURE 4.3.1-1. CONCEPT B, RAM VENTILATION WITH ADDED DUMP VALVE

4.3.3 CONCEPT B: DESCRIPTIONS AND COST ESTIMATES

4.3.3.1 BOEING 707 CHANGES

4.3.3.1.1 Ram Ventilation (see Figure 4.3.3.1-1)

Install a single fan (diameter 8 inches maximum and 10 inches length maximum) in the air conditioning distribution duct bay to provide 2400 cfm total flow with the airplane stopped at sea level; passenger cabin flow will be 2160 cfm.

Install 4 inch diameter ducting to connect the fan discharge with the existing distribution manifold.

Install ducting between L.H. ram air duct and the inlet of the fan. This will include an electric motor driven shut-off valve.

Install control in the cockpit to operate the fan and the shut-off valve.

Install wiring to provide battery power to the fan and AC power to the valve.

Install wiring between the cockpit and the fan and valve.

4.3.3.1.2 Added Dump Valve

This addition will be the same as the dual outflow valve per Paragraph 4.2.3.1.2.

The total cost (non-recurring and per-airplane) to incorporate these changes by retrofit of the current U.S. fleet of 36 airplanes is estimated to be about $2,000,000.

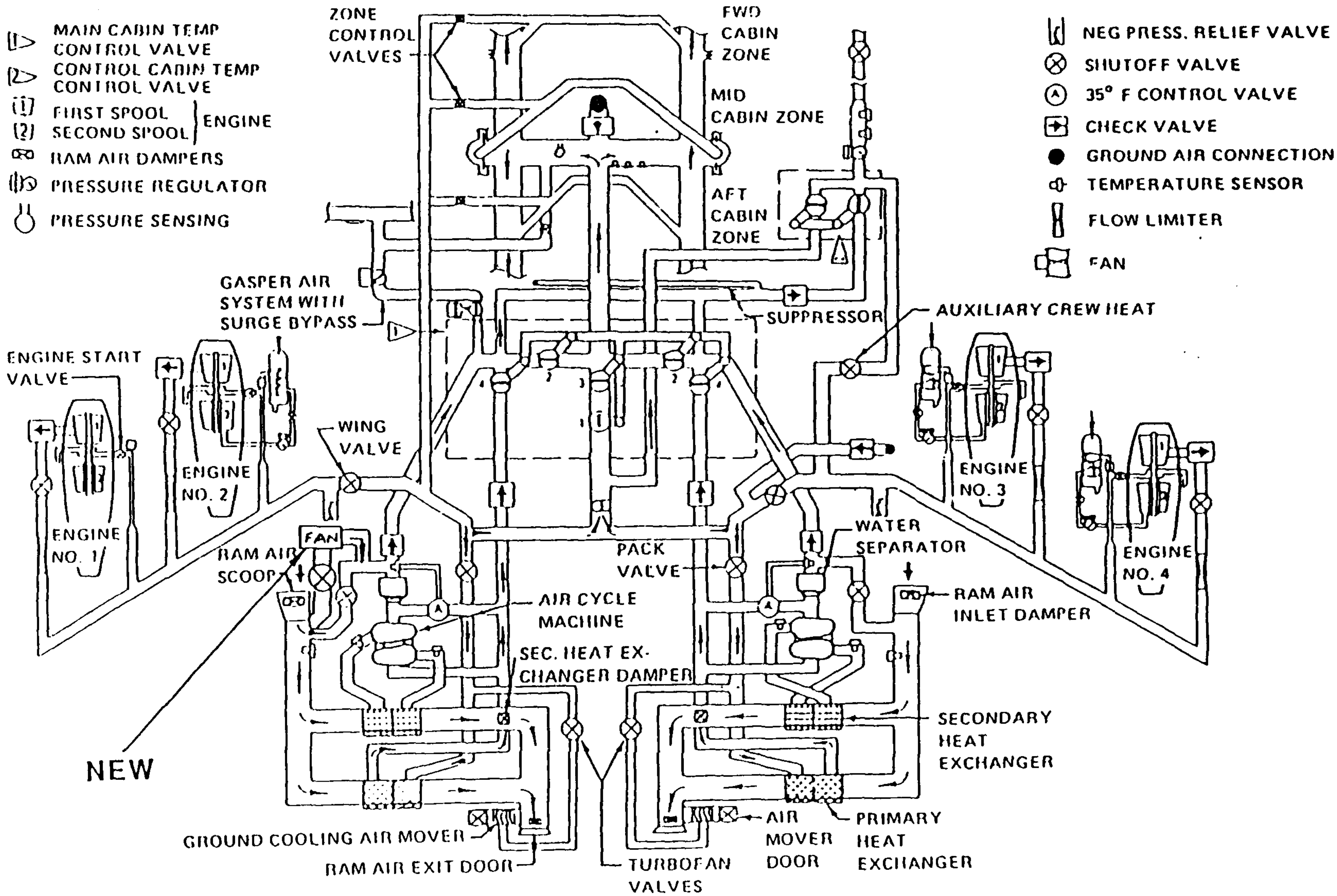


FIGURE 4.3.3.1-1. CONCEPT B, 707, RAM VENTILATION

4.3.3.2 BOEING 727-100 CHANGES

4.3.3.2.1 Ram Ventilation (see Figure 4.3.3.2-1)

Install a single fan (dia 8 inches max and 10 inches length max.) in the air conditioning distribution duct bay to provide 1800 cfm total flow with the airplane stopped at sea level; passenger cabin flow will be 1647 cfm.

Install 4" ducting to connect the fan discharge with the existing distribution manifold.

Install ducting between L. H. ram air duct and the inlet of the fan. This will include an electric motor driven shut-off valve.

Install controls in the cockpit to operate the fan and the shut-off valve.

Install wiring to provide battery power to the fan and AC power to the valve.

Install wiring between the cockpit and the fan and valve.

4.3.3.2.2 Added Dump Valve

This addition will be the same as the dual outflow valve per Paragraph 4.2.3.2.2.

The total cost (non-recurring and per-airplane) to incorporate these changes by retrofit of the current U.S. fleet of 344 airplanes is estimated to be about $14,200,000.

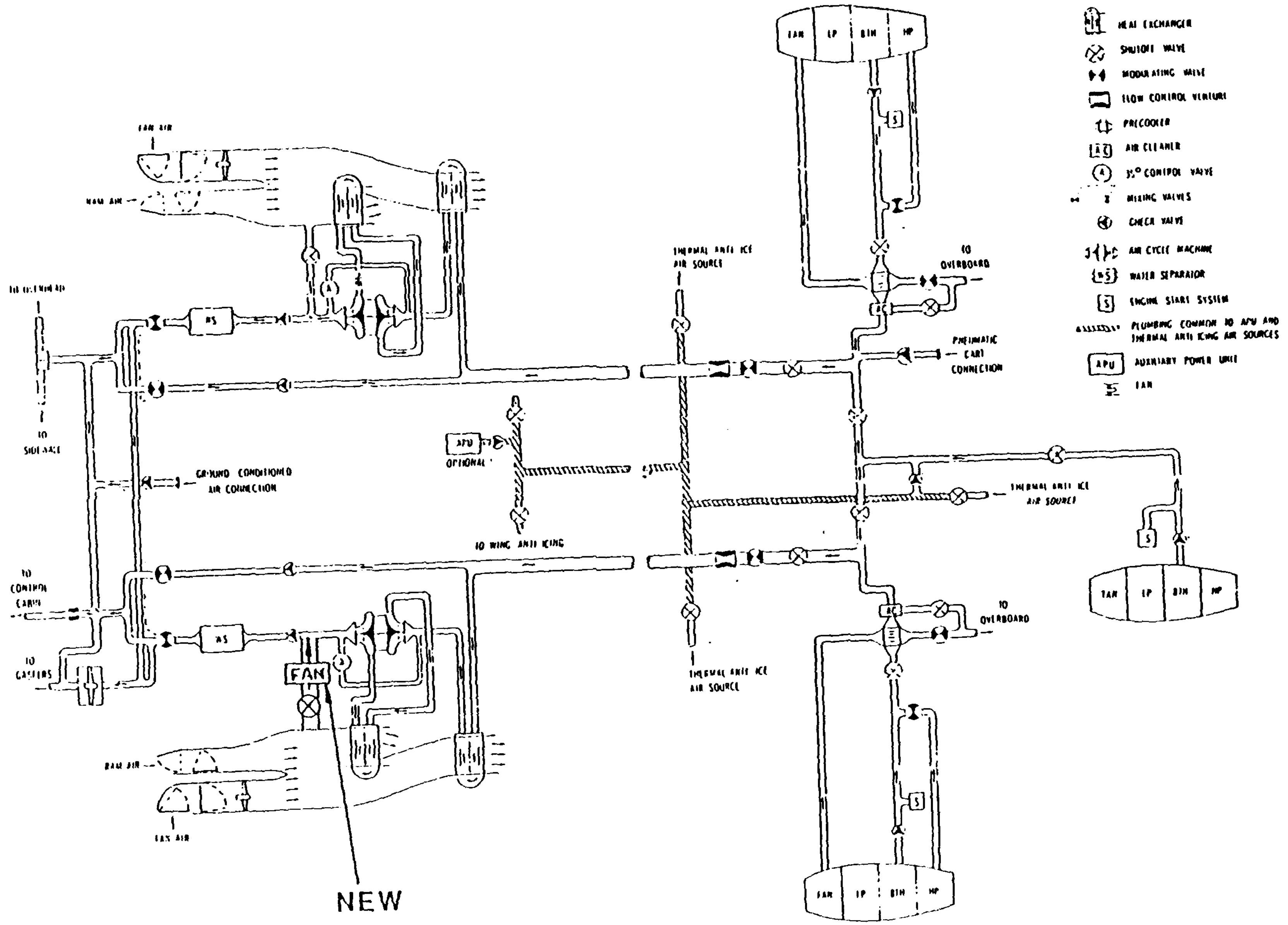


FIGURE 4.3.3.2-1. CONCEPT B, 727-100, RAM VENTILATION

4.3.3.3 BOEING 727-200 CHANGES

4.3.3.3.1 Ram Ventilation (see Figure 4.3.3.3-1)

Install a single fan (dia 8 inches max and 10 inches length max.) in the air conditioning distribution duct bay to provide 1800 cfm total flow with the airplane stopped at sea level; passenger cabin flow will be 1647 cfm.

Install 4" dia ducting to connect the fan discharge with the existing distribution manifold.

Install ducting between L.H. ram air duct and the inlet of the fan. This will include an electric motor driven shut-off valve.

Install controls in the cockpit to operate the fan and the shut-off valve.

Install wiring to provide battery power to the fan and AC power to the valve.

Install wiring between the cockpit and the fan and valve.

4.3.3.3.2 Added Dump Valve

This addition will be the same as the dual outflow valve per Paragraph 4.2.3.3.2.

The total cost (non-recurring and per-airplane) to incorporate these changes by retrofit of the current U.S. fleet of 853 airplanes is estimated to be about $30,800,000.

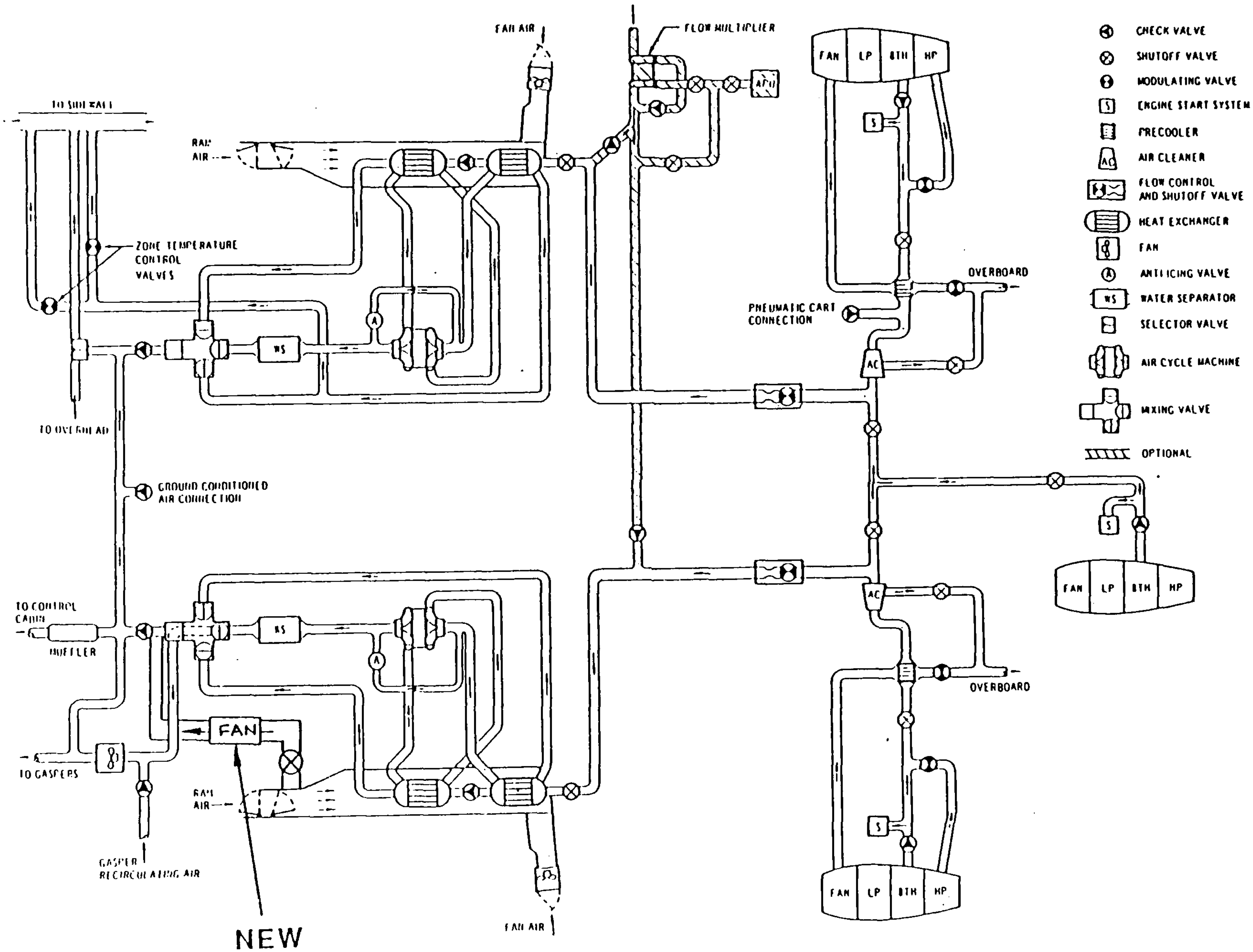


FIGURE 4.3.3.3-1. CONCEPT B, 727-200, RAM VENTILATION

4.3.3.4 BOEING 737 CHANGES

4.3.3.4.1 Ram Ventilation

Both air conditioning packs will be modified to allow ambient air to be taken from the current ram air ducts just aft of the inlets. The new components will include two 6 inch diameter shut-off valves, two DC powered 2.8 KW fans and ducts to carry the air to the pack outlet ducts just downstream of the water separators (see figures 4.3.3.4-1 and 4.3.3.4-2). This change will provide 2500 cfm total flow with the airplane stopped at sea level; passenger cabin flow will be 2284 cfm.

Electrical cables will be added to supply DC power to the new fans via the generators and the existing standby battery.

Electrical control logic will be added to cause fans to switch from generator power to battery power upon engine shutdown.

Cockpit controls will be added to command the new shut-off valves and fans.

Electrical wiring will be added between the new and modified components and the cockpit.

4.3.3.4.2 Added Dump Valve

A twin of the current cabin pressure control system outflow valve will be added in the lower fuselage, right hand side, in the vicinity of the E/E bay. This added valve will be controlled to provide a simple open or closed exhaust port.

The structure around the added valve will be modified to support the mounting flange of the added valve and maintain fuselage strength.

Cockpit controls will be added to command the added valve open or closed.

Electrical wiring will be added between the added valve and the cockpit.

The total cost (non-recurring and per-airplane) to incorporate these changes by retrofit of the current U.S. fleet of 641 airplanes is estimated to be about $25,300,000. For future production of 727 airplanes through 1992, the cost is estimated to be about $29,000,000.

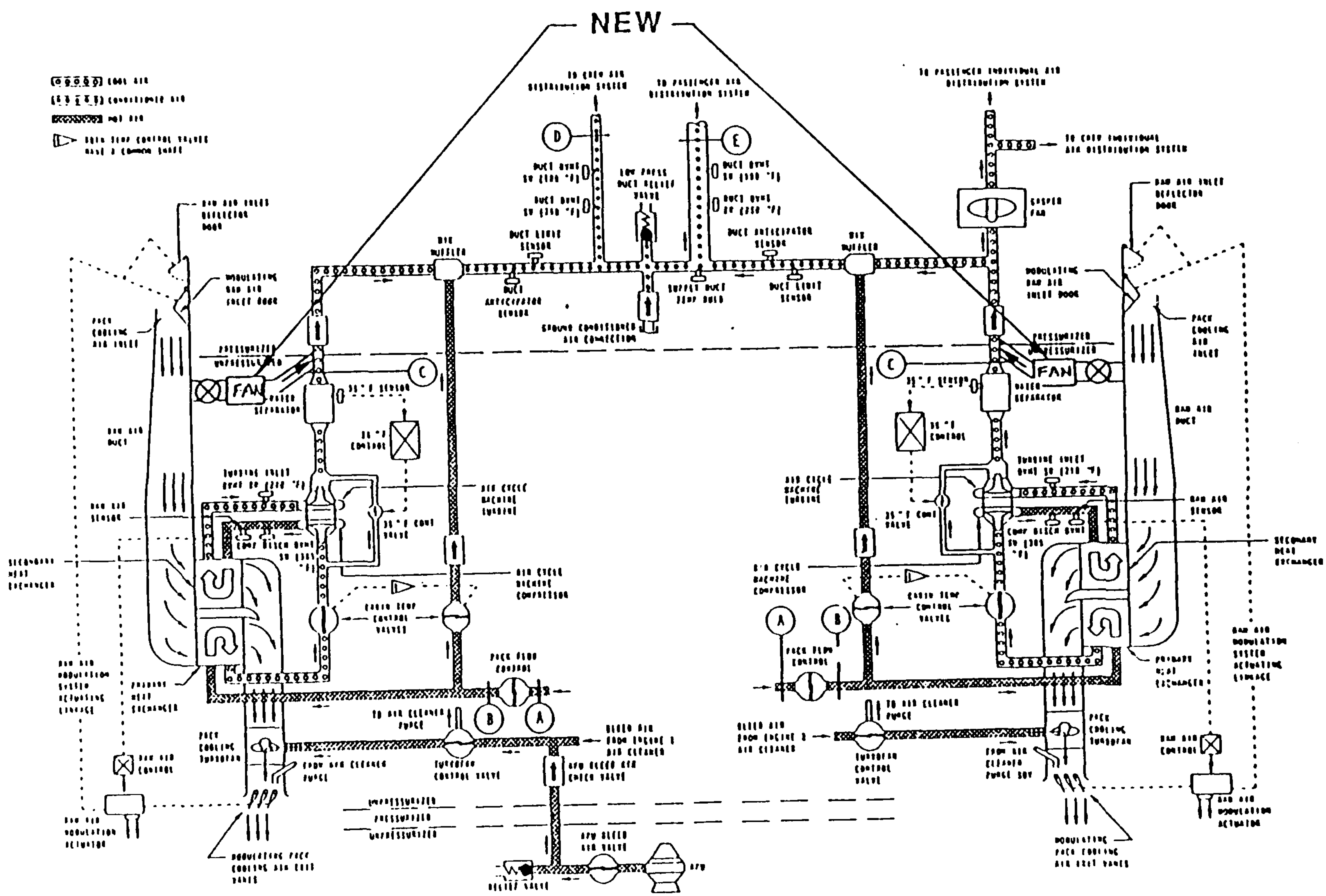


FIGURE 4.3.3.4-1. CONCEPT B, 737-100/200, RAM VENTILATION

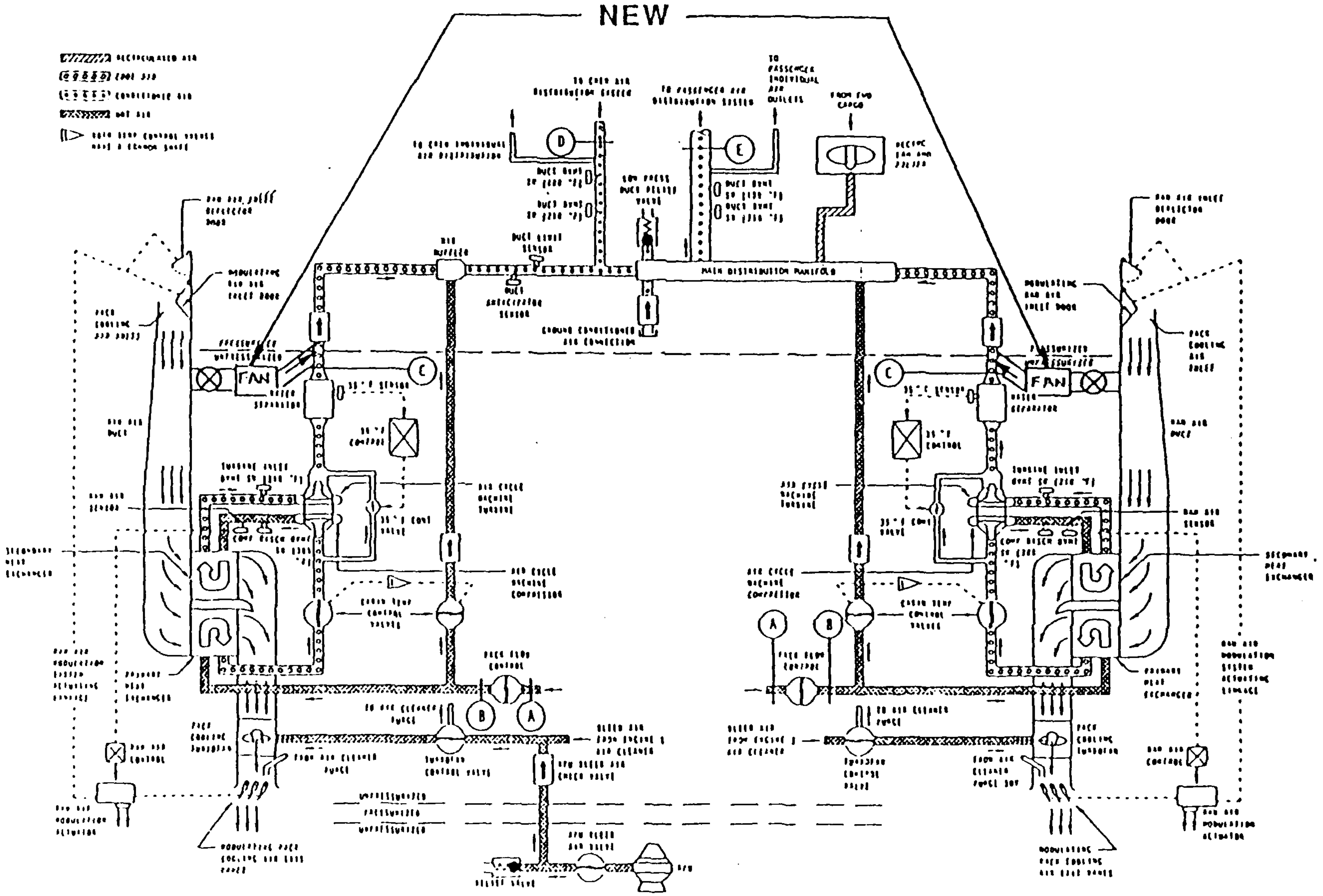


FIGURE 4.3.3.4-2. CONCEPT B, 737-300, RAM VENTILATION

4.3.3.5 BOEING 747 CHANGES

4.3.3.5.1 Ram Ventilation

All three (3) air conditioning packs will be modified to allow ambient air to be taken from the current ram air duct just aft of the inlet (see Figure 4.3.3.5-1). The new components will include three 9-inch diameter shut-off valves, three DC powered 6 K.W. fans and ducts to carry the air to the pack outlet duct just downstream of the water separators This change will provide 8,000 cfm total flow with the airplane stopped at sea level; passenger cabin flow will be 7476 cfm.

New batteries will be installed to power the above fans.

Cockpit controls will be added to command the ram inlets and exits and the new shut-off valves and fans.

Electrical wiring will be added between the new and modified components and the cockpit.

4.3.3.5.2 Added Dump Valve

This addition will be the same as the dual outflow valve per Paragraph 4.2.3.5.2.

The total cost (non-recurring and per-airplane) to incorporate these changes by retrofit of the current U.S. fleet of 167 airplanes is estimated to be about $12,900,000. For future production of 226 airplanes through 1992, the cost is estimated to be about $22,700,000.

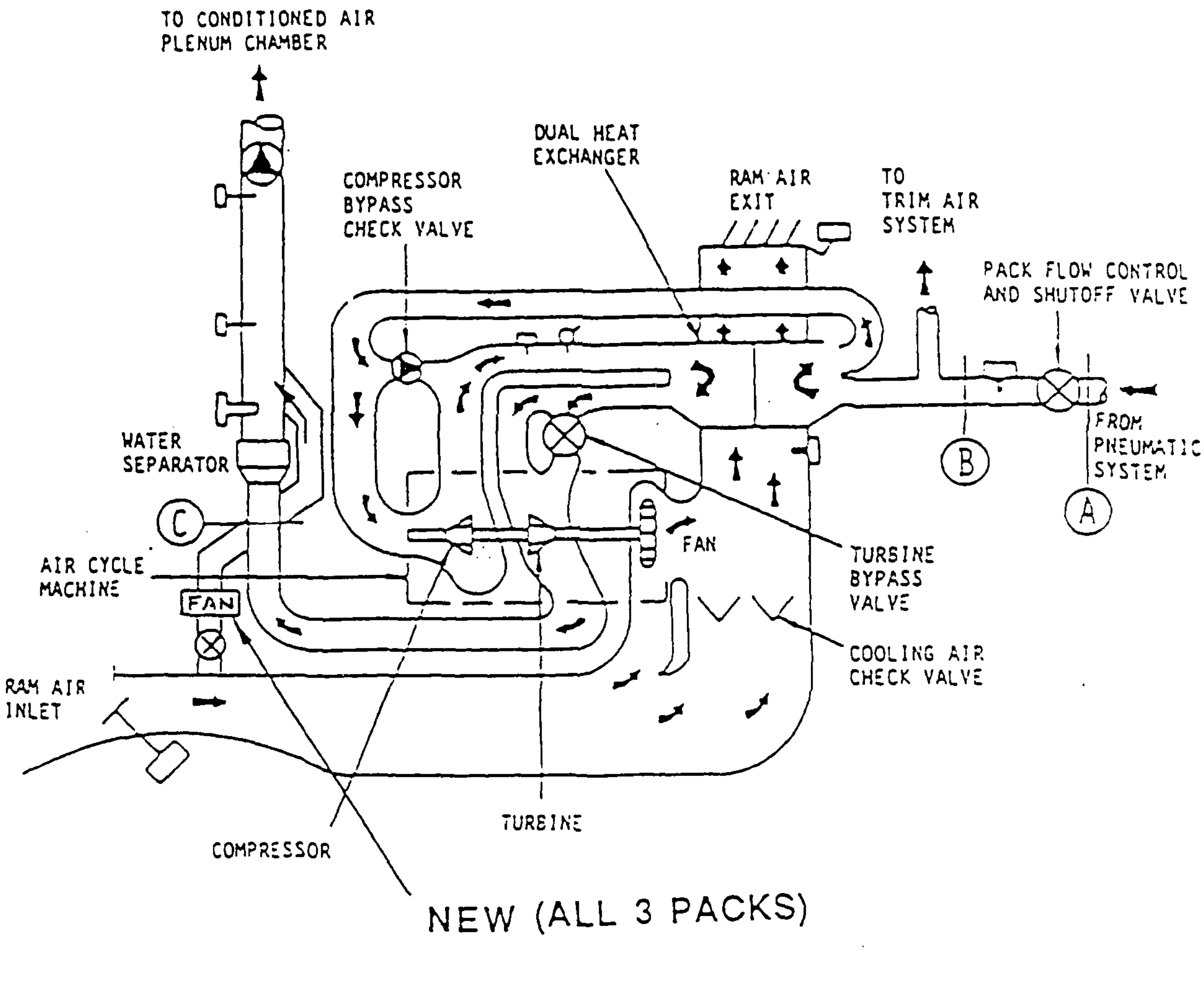


FIGURE 4.3.3.5-1. CONCEPT B, 747, RAM VENTILATION

4.3.3.6 BOEING 757 CHANGES

4.3.3.6.1 Ram Ventilation

Both air conditioning packs will be modified to allow ambient air to be taken from the current ram air ducts just aft of the inlets (see Figure 4.3.3.6-1). The new components will include two 8 inch diameter shutoff valves, two DC powered 2.7 KW fans and ducts to carry the air to the pack outlet ducts just downstream of the condensers. This change will provide 3860 cfm total flow with the airplane stopped at sea level; passenger cabin flow will be 3313 cfm.

Electrical cables will be added to supply DC power to the new fans via the generators and the existing standby battery.

Electrical control logic will be added to cause fans to switch from generator power to battery power upon engine shutdown.

Cockpit controls will be added to command the new shutoff valves and fans.

Electrical wiring will be added between the new and modified components and the cockpit.

4.3.3.6.2 Add Dump Valve

A twin of the current cabin pressure control system outflow valve will be added in the lower fuselage, left hand side, in the vicinity of the E/E bay. This added valve will be controlled to provide a simple open or closed exhaust port.

The structure around the added valve will be modified to support the mounting flange of the added valve and maintain fuselage strength.

Cockpit controls will be added to command the added valve open or closed.

Electrical wiring will be added between the added valve and the cockpit.

The total cost (non-recurring and per-airplane) to incorporate these changes by retrofit of the current U.S. fleet of 98 airplanes is estimated to be about $5,400,000. For future production of 187 airplanes through 1992, the cost is estimated to be about $10,100,000.

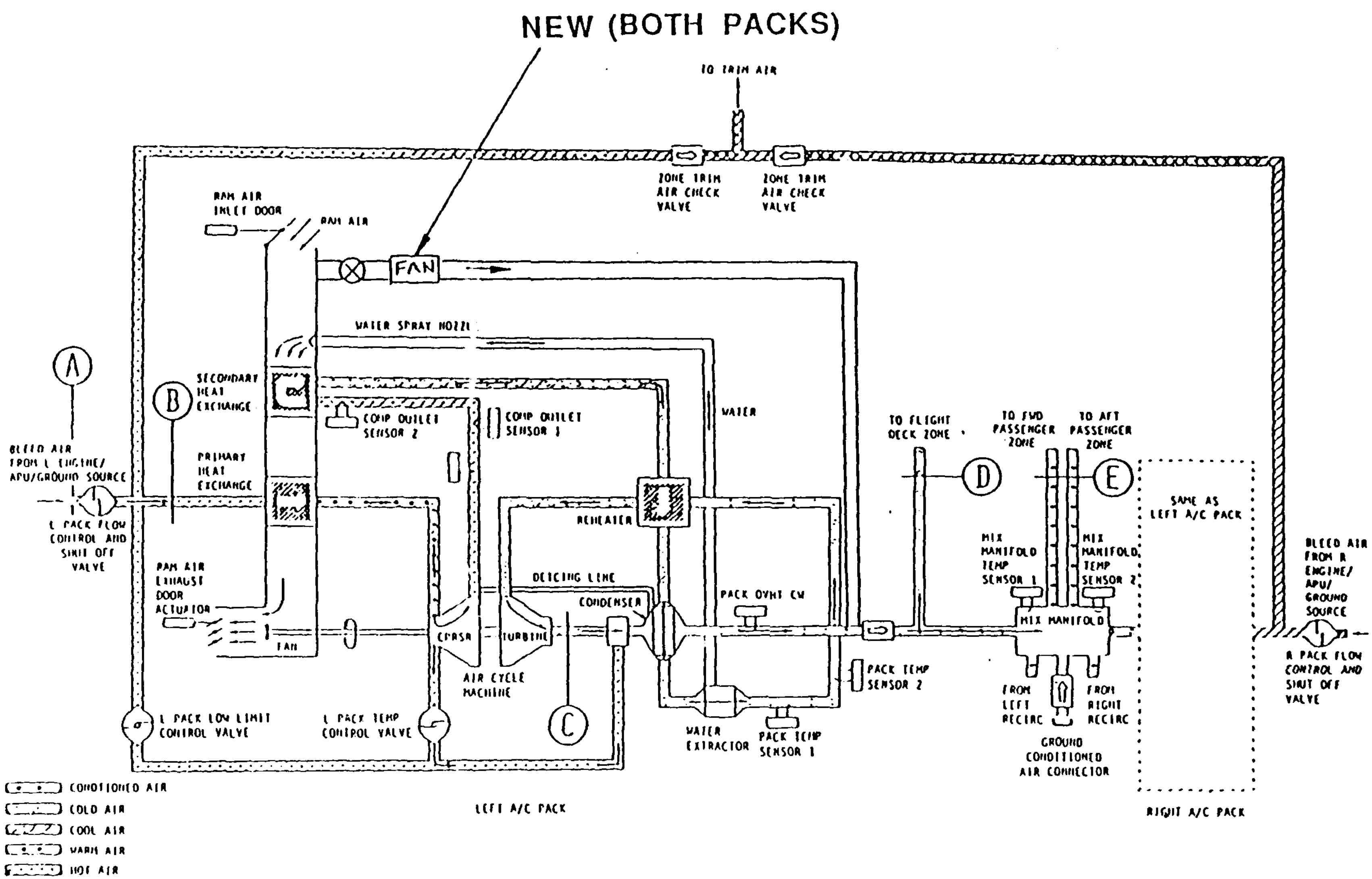


FIGURE 4.3.3.6-1. CONCEPT B, 757, RAM VENTILATION

4.3.3.7 BOEING 767 CHANGES

4.3.3.7.1 Ram Ventilation

Both air conditioning packs will be modified to allow ambient air to be taken from the current ram air duct just aft of the inlet (see Figure 4.3.3.7-1). The new components will include (2) 7-inch diameter shutoff valves, (2) DC-powered 5 K.W. fans and ducts to carry the air to the pack outlet duct just downstream of the water separators. This change will provide 5,000 cfm total flow with the airplane stopped at sea level; passenger cabin flow will be 4432 cfm.

New batteries will be installed to power the above fans.

Cockpit controls will be added to command the ram inlets and exits and the new shutoff valves and fans.

Electrical wiring will be added between the new and modified components and the cockpit.

4.3.3.7.1 Added Dump Valve

This addition will be the same as the dual outflow valve per Paragraph 4.2.3.7.2.

The total cost (non-recurring and per-airplane) to incorporate these changes by retrofit of the current U.S. fleet of 87 airplanes is estimated to be about $4,700,000. For future production of 212 airplanes through 1992, the cost is estimated to be about $11,100,000.

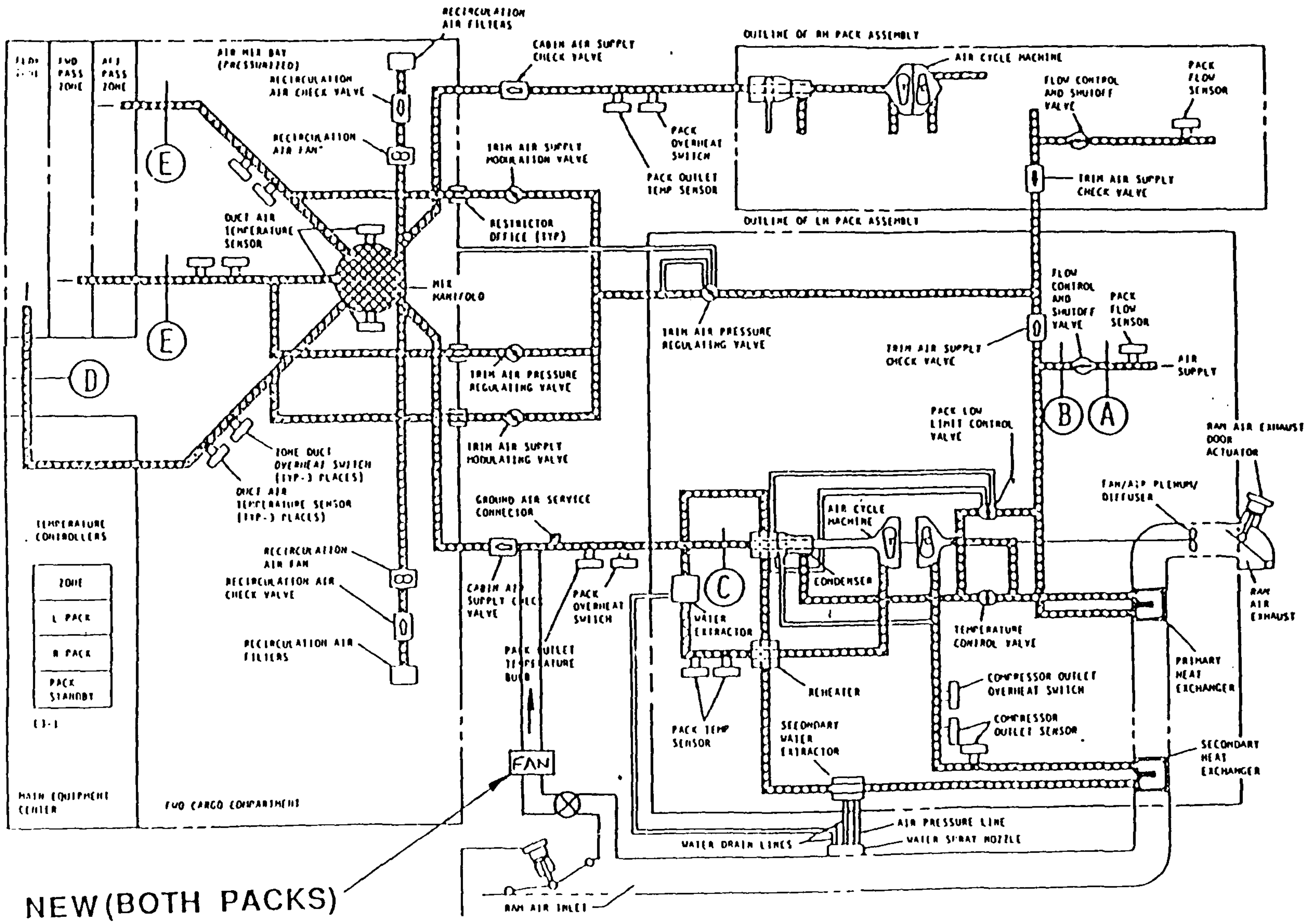


FIGURE 4.3.3.7-1. CONCEPT B, 767, RAM VENTILATION

4.3.3.8 DOUGLAS DC-8

4.3.3.8.1 GENERAL

During flight with both packs off, ram air can be used for cabin ventilation. This air is supplied from the ram air scoop of the left cooling system through a manually actuated shutoff valve. This valve is manually operated by a push-pull T-handle located on the flight compartment floor behind the second observer's seat.

4.3.3.8.2 CHANGES

4.3.3.8.2.1 Ram Ventilation

Additional ram air cabin ventilation system will be added.

DC-powered fan(s) will be added (see Figure 4.3.3.8-1) to provide approximately 2,000 cfm total flow with the airplane stopped at sea level; passenger cabin flow will be 1,756 cfm.

The current ram air controls will be modified to accommodate the additional valves.

Cockpit controls will be added to command the valves and fan(s).

Electrical wiring will be added between the new and modified components and the cockpit.

4.3.3.8.2.2 Added Dump Valve

For this study, to provide an additional exhaust port, a twin of the current pressure control outflow valve will be added. The location of the added valve will be in the fuselage, aft of the forward cargo compartment (as shown in Figure 4.2.3.8-2).

The structure around the added valve will be modified to support the mounting flange of the added valve and maintain fuselage strength.

Cockpit controls will be added to command the added valve open or closed.

Electrical wiring will be added between the added valve and the cockpit.

The total cost (non-recurring and per-airplane) to incorporate these changes by retrofit of the current U.S. fleet of 188 airplanes is estimated to be about $38,500,000.

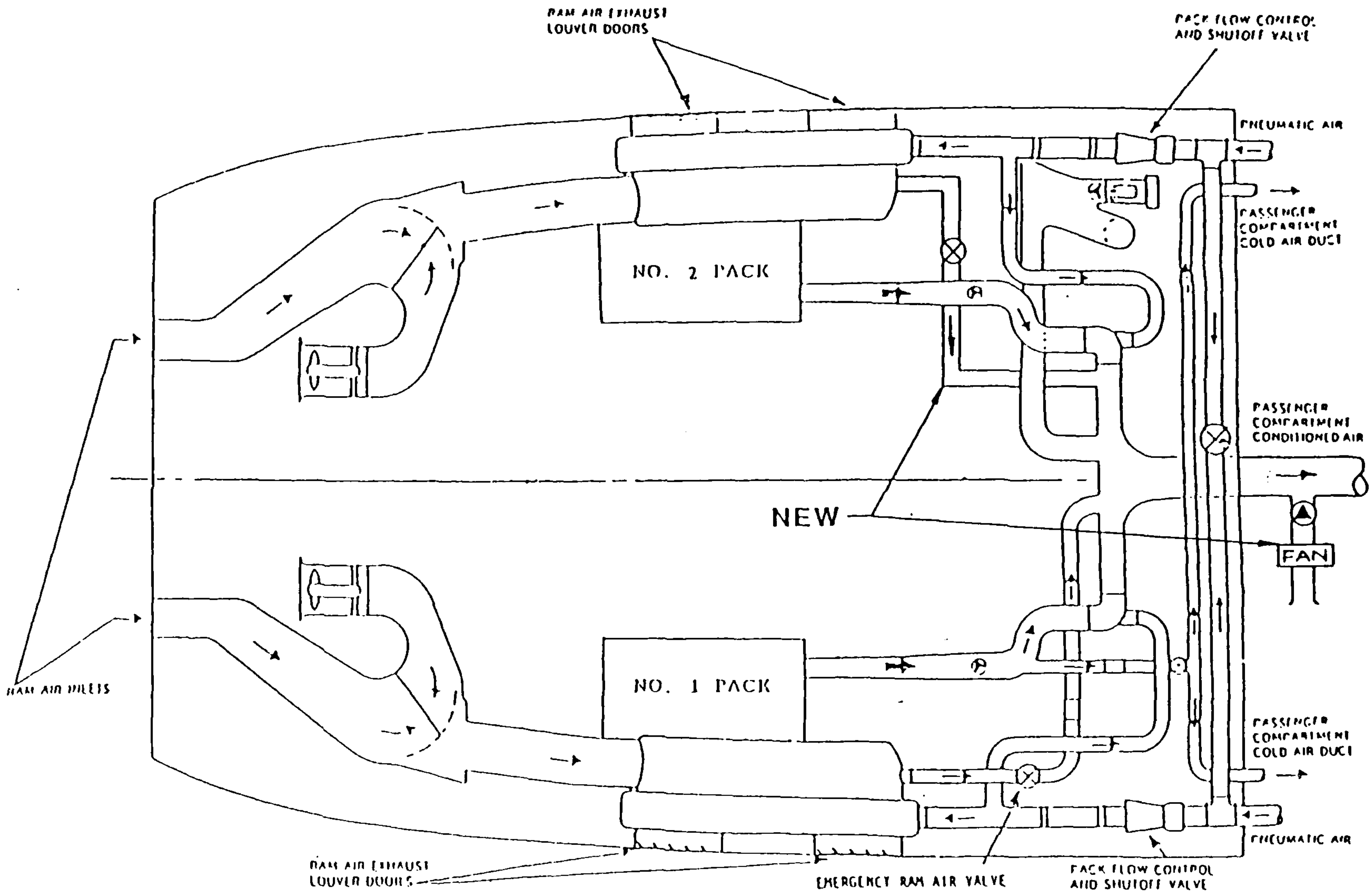


FIGURE 4.3.3.8-1. CONCEPT B, DC-8, RAM VENTILATION

4.3.3.9 DOUGLAS DC-9/MD-80

4.3.3.9.1 GENERAL

Ram air is supplied to the cabin and cockpit distribution duct for ventilation purposes during unpressurized flight and when air conditioning packs are not in operation. A ram air valve is located in a duct that interconnects the right-hand heat exchanger ram air inlet ducting to the cabin and cockpit distribution ducting.

4.3.3.9.2 CHANGES

4.3.3.9.2.1 Ram Ventilation

An additional ram air valve will be added.

A DC-powered fan will be added (see Figure 4.3.3.9-1) to provide approximately 2,000 cfm total flow with the airplane stopped at sea level; passenger cabin flow will be 1,747 cfm.

Cockpit controls will be added to run the fan.

Electrical wiring will be added between the new and modified components and the cockpit.

4.3.3.9.2.2 Added Dump Valve

For this study, to provide an additional exhaust port, a twin of the current pressure control outflow valve will be added. The location of the added valve will be in the left-hand side of the fuselage near the front end of the forward cargo compartment (as shown in Figure 4.2.3.9-2).

The structure around the added valve will be modified to support the mounting flange of the added valve and maintain fuselage strength.

Cockpit controls will be added to command the added valve open or closed.

Electrical wiring will be added between the added valve and the cockpit.

The total cost (non-recurring and per-airplane) to incorporate these changes by retrofit of the current U.S. fleet of 699 airplanes is estimated to be about $172,800,000. For future production of 502 airplanes through 1992, the cost is estimated to be about $ 72,000,000.

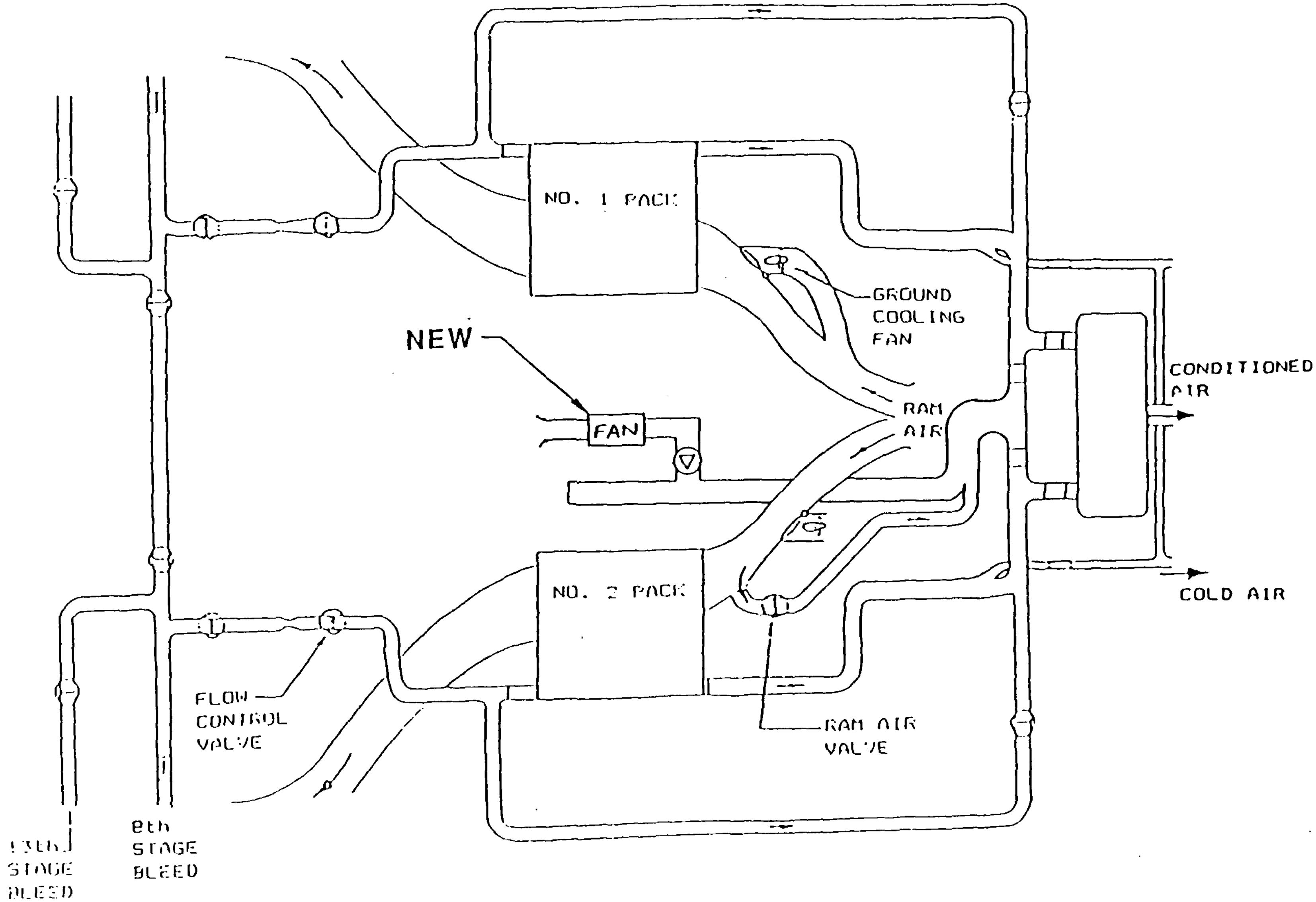


FIGURE 4.3.3.9-1. CONCEPT B, DC-9, RAM VENTILATION

4.3.3.10 DOUGLAS DC-10

4.3.3.10.1 GENERAL

The ram air cabin ventilation system provides ventilating air to the cockpit and cabin when all three of the air conditioning packs are inoperative. The system is located in the left air conditioning compartment and consists of an on-off valve and ducting which connects the left hand ram air scoop to the conditioned air duct downstream of pack No. 1.

4.3.3.10.2 CHANGES

4.3.3.10.2.1 Ram Ventilation

An additional ram air cabin ventilation system will be added.

DC-powered fan(s) will be added (see Figure 4.3.3.10-1) to provide approximately 6,000 cfm total flow with the airplane stopped at sea level; passenger cabin flow will be 5,465 cfm.

The current ram air controls will be modified to accommodate additional valves.

Cockpit controls will be added to command the valves and fan(s).

Electrical wiring will be added between the new and modified components and the cockpit.

4.3.3.10.2.2 Added Dump Valve

For this study, to provide an additional exhaust port, a twin of the current pressure control outflow valve will be added. The location of the added valve will be in the left-hand side of the fuselage in the aft end of the aft cargo compartment (as shown in Figure 4.2.3.10-2).

The structure around the added valve will be modified to support the mounting flange of the added valve and maintain fuselage strength.

Cockpit controls will be added to command the added valve open or closed.

Electrical wiring will be added between the added valve and the cockpit.

The total cost (non-recurring and per-airplane) to incorporate these changes by retrofit of the current U.S. fleet of 190 airplanes is estimated to be about $57,800,000 For future production of 200 airplanes of derivative models through 1992, the cost is estimated to be about $ 42,800,000.

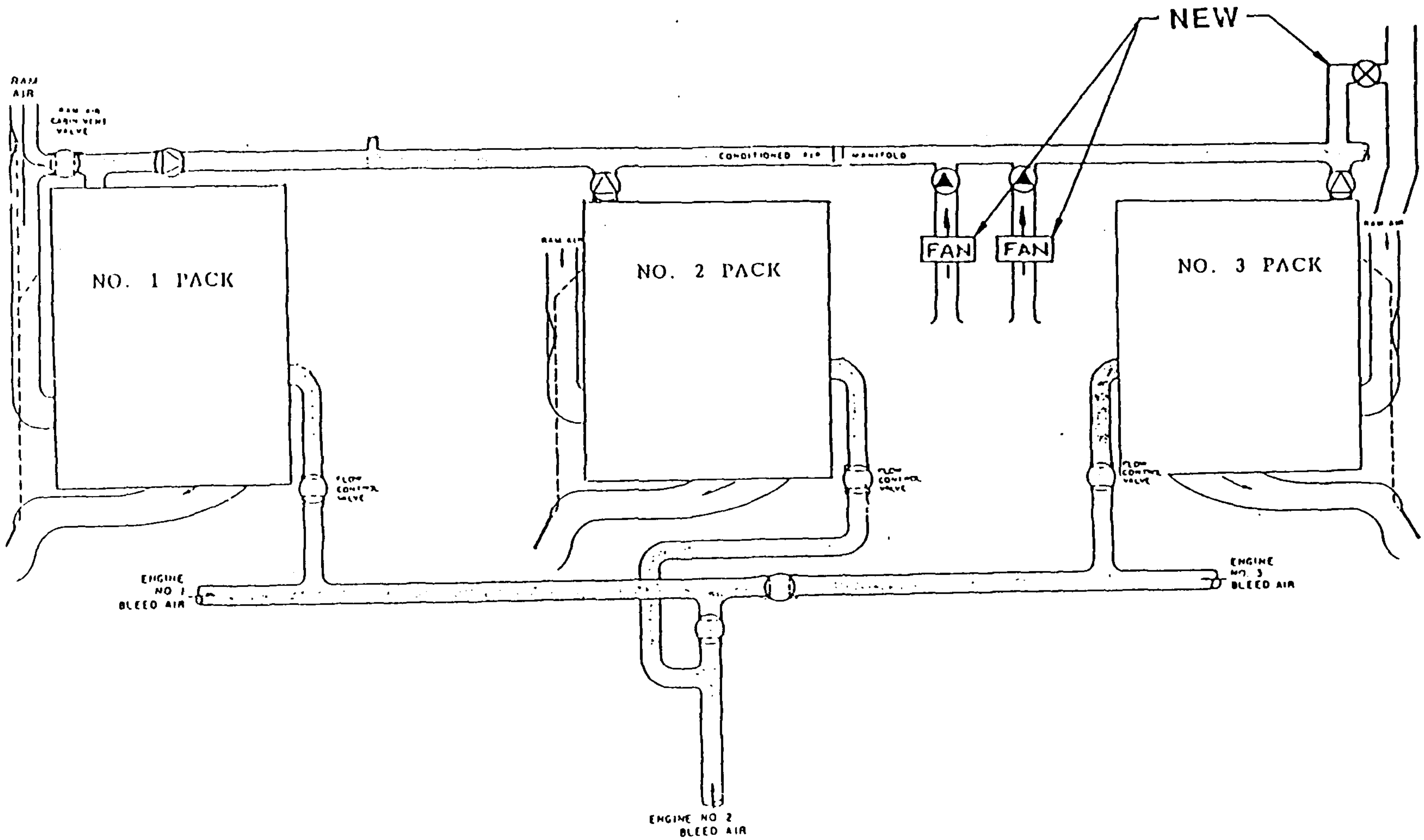


FIGURE 4.3.3.10-1. CONCEPT B, DC-10, RAM VENTILATION

5. EFFECTIVENESS PARAMETER

5.1 GENERAL

As required for this study, a smoke venting effectiveness "parameter" has been derived to predict the venting performance of current airplanes and the enhancement concepts. The effectiveness parameter measures the venting performance by calculating (1) the maximum concentration of the smoke cloud in the passenger cabin and (2) the fraction of the passenger cabin that is free of smoke. An airplane's venting performance would be considered enhanced by any change that decreases smoke concentration or increases the length smoke-free. Five sets of equations have been derived to calculate the parameter for all of the scenarios, airplane models and enhancement concepts in this study. This report section explains the derivation and use of the equation sets and shows that some of the equations are partially validated by the results of past fires and airplane tests.

5.2 EQUATION DERIVATIONS

5.2.1 NOMENCLATURE

A	=	Air inflow volumetric flow rate (cfm)
CIN	=	Concentration of the incoming smoke (lb/cu ft)
CMAX	=	Maximum concentration of the smoke cloud in the occupied cabin volume (lb/cu ft)
BA	=	Outflow volumetric flow rate in the aft half of the cabin per unit length) (cfm/decimal percent of cabin length)
BF	=	Same as BA except in the forward half of the cabin
LC	=	Length of smoke cloud in the cabin (decimal percent of cabin length)
LCA	=	Length of smoke cloud aft of the smoke injection region (decimal percent of cabin length)
LCF	=	Same as LCA except forward of the smoke injection region
LSF	=	Length of the cabin that is smoke-free (decimal percent of cabin length)
LSI	=	Length over which the incoming smoke is injected into the passenger cabin (decimal percent of cabin length)
R	=	Outflow balance ratio defined as BA/BF (unitless)
S	=	Smoke injection volumetric flow rate (cfm)

5.2.2 SCENARIO 1 EQUATION SET

The basic premise for deriving these equations is that the incoming smoke will mix in the passenger cabin with the air conditioning air inflow and gradually spread into a steady-state cloud such that the air/smoke mixture leaving the cabin is venting smoke at a weight rate equal to the weight rate of smoke inflow. This premise applies for airplanes with air conditioning nozzles located at the highest point of the cabin ceiling so that the smoke, regardless of buoyancy, is assumed to be forced to mix and spread throughout the height and width of the cabin. Airplanes with other nozzle locations are covered in Paragraph 5.2.4.

The set of equations for scenario 1 are shown on Figure 5-1 which also schematically depicts the cabin air flows, the smoke inflow and the smoke cloud concentration profile in a simplified side view of a passenger cabin. The seven simultaneous equations predict the steady-state location and concentration profile of the smoke cloud in the passenger cabin. The air inflow from the air conditioning nozzles is assumed to be distributed evenly over the entire cabin length.

Equation (1)

$$A + S = (BF+BA)/2 \tag{1}$$

indicates that the average of the two outflows must equal the total inflow.

Equation (2)

$$R = BA/BF \tag{2}$$

defines the outflow balance ratio R which has been estimated to vary between 2.77 and 0.19 depending on the airplane model and on which combinations of the forward and aft outflow valves are open. The R values used for this study are listed on Figure 6-1.

Equation (3)

$$CMAX = CIN\ S/(S+A(LSI+0.05)) \tag{3}$$

calculates the maximum concentration of the smoke cloud in the passenger cabin. For scenario 1, LSI is fixed at 0.2; for scenarios 2, 3 and 4 LSI is zero. The numerator on the right hand side of the equation is the weight rate that smoke particles are entering the cabin. The denominator is the total volume rate of air flow that mixes with the smoke particles. The term (LSI + 0.05) reflects the assumption that the incoming smoke will spread into approximately 5% more cabin length than the actual injection length before it mixes with the cabin air. As shown on Figure 5-1, the CMAX concentration is assumed to be constant over the length LSI + 0.05.

Equation (4)

$$S\ CIN = (0.5\ LCF\ BF\ CMAX) + ((LSI + 0.05)A\ CMAX) + (0.5\ LCA\ BA\ CMAX) \tag{4}$$

is based on the assumptions that the steady-state smoke cloud concentration will decay linearly over distances LCF and LCA forward and aft of the smoke injection region and that the smoke cloud concentration profile shown in the figure represents the conditions throughout the height and width of the cabin. The left side of the equation gives the weight rate of smoke particle inflow and the left side gives the outflow rate.

Equation (5)

$$R = LCA/LCF \tag{5}$$

is a simplified function that accounts for the fact that the cloud dimensions LCA and LCF will be longer or shorter depending on the axial airflow velocity in the passenger cabin which, in turn, depends on the outflow balance ratio R. Equations (4) and (5) are based on assumptions that do not account for the possibility that some puffs or localized trails of smoke may escape from the smoke cloud in the direction of any axial airflow that may exist in the passenger cabin. It is considered appropriate to ignore effects such as these because their impact is relatively small and equal for the concepts in this study.

Equations (6) and (7)

$$LC = LCF + (LSI + 0.05) + LCA \tag{6}$$

$$LSF = 1 - LC \tag{7}$$

determine the value of LSF, the fraction of the passenger cabin length that is free of smoke.

In the listing on Figure 5-1 under the heading "Variable Sheet", the values S, CIN, LSI, A and R are the inputs as indicated by I in the status (St) column. The outputs (indicated by 0) are the result of solving the seven simultaneous equations.

5.2.3 SCENARIOS 2, 3 AND 4 EQUATION SETS

The equation sets for scenarios 2, 3 and 4 are shown on Figures 5-2, 5-3 and 5-4. The derivation rationale for these sets is the same as for scenario 1 except for the changes dictated by the different locations of smoke injection. For scenarios 2 and 3, equation (4) uses BA in all of the terms for the smoke particle outflow. Similarly, for scenario 4, the equation uses BF for all outflow terms. For scenarios 3 and 4, equation (5) is unnecessary and eliminated because the smoke is injected at the end of the cabin and thus has only one segment with the linear decay profile.

5.2.4 EQUATION SET NO. 5

The preceding four equation sets are applicable to all airplane models provided that the air conditioning nozzles are located at the highest point of the cabin ceiling where buoyant smoke will be forced to mix and spread throughout the height and width of the cabin. However, the Boeing 707 and 747 and the Douglas DC-8 and DC-9 airplanes do not have air conditioning nozzles at the highest ceiling location. When these airplanes are subjected to the buoyant smoke from scenarios 2 or 3, the equation set No. 5 shown on Figure 5- 5 is applicable. As shown on the figure, it is assumed that buoyant smoke injected at the ceiling will fill the "tunnel" over the entire length of the cabin below the ceiling. When the upper volume is filled, the smoke will enter the lower (occupied) cabin volume at the smoke inflow rate S and mix with the air conditioning inflow A.

Equation (8)

$$CMAX = CIN\ S/(A+S) \tag{8}$$

calculates the maximum smoke cloud concentration CMAX in the lower (occupied) cabin volume. The numerator on the right hand side of the equation is the weight rate that smoke particles are entering the volume. The denominator is the total volume rate of air flow that mixes with the smoke particles. For this equation set, the length smoke free LSF is set equal to zero to account for the fact that the cloud will be present throughout the entire passenger cabin.

5.3 EQUATION VALIDATION

5.3.1 PAST FIRE VALIDATIONS

Validation of the preceding smoke venting effectiveness equations is shown by comparison with the results of some past fire accidents. The fire/smoke locations reported in the Varig 707, the Saudi L-1011 and the Air Canada DC-9 fires (see Paragraphs 2.5.1, 2.5.2 and 2.5.3) correspond to the scenario 3 equation set. Since two of the fires (Varig 707 and Air Canada DC-9) involved airplanes with air conditioning nozzle locations that allow undiluted smoke to "tunnel" along the entire ceiling length, equation set No. 5 would apply if the smoke was hot and buoyant. Since smoke "tunneling" was not reported during the early stages of these fires, the smoke must have been cool and neutrally buoyant. This means that scenario 3 equation set applies for all three fires and allows a comparison of the length smoke free LSF as a function of ventilation air inflow rate A as shown on Figure 5-6. The solid line shows the results predicted by the equation set with the smoke rate S = 200 cfm; for

comparison, the dashed lines show the predictions with smoke rates of 100 and 400 cfm. The results from the three past fires show close agreement with the analytic predictions.

5.3.2 TEST VALIDATIONS

Validation of the equations is also shown by comparison with the results of some previous flight tests. The non-certification tests (see Paragraph 2.4) can be represented by scenario 3 equation set with the length of smoke injection LSI set at 0.10 to account for the fact that the smoke generator "throws" the smoke several feet before it begins to mix with the cabin air. The predictions of the equation set and the actual test results are shown on Figure 5-7. The 707 test shows good agreement for the effect of closing the forward outflow valve. The 727 and 737 tests confirm the general trend that the smoke free length decreases when the air inflow rate is decreased.

While the above comparisons show at least partial validation of the equation set for scenario 3, there are no past fires or direct test data to validate the other equation sets. Some of the other equation sets give higher than expected predictions of smoke free length for cases involving forward smoke scenarios with the aft outflow valve open. The open aft outflow valve tends to cause aftward axial flow that might be expected to spread smoke through more of the passenger cabin length than predicted by the equations. Additional tests of such cases could show if modifications are needed to provide equation sets that are completely valid.

================================ Equation Sheet =======================

```
St Equation
-- --------
   A+S=(BF+BA)/2
   R=BA/BF
   CMAX=CIN*S/(S+A*(LSI+.05))
   S*CIN=(.5*LCF*BF*CMAX)+(LSI+.05)*A*CMAX+(.5*LCA*BA*CMAX)
   R=LCA/LCF
   LC=LCF+(LSI+.05)+LCA
   LSF=1-LC
```

================================ Variable Sheet =======================

St	Name	Value	Dsp Unit	Cal Unit	Comments
I	S	200		CFM	SMOKE INFLOW
I	CIN	.00045		LB/CU.FT	SMK CONCEN IN
I	LSI	.2	FIXED	%(DEC)	LENGTH SMOKE IN
I	A	2700		CFM	AIR INFLOW
I	R	1		-	BALANCE RATIO
O	CMAX	.000102		LB/CU.FT	SMK CONCEN MAX
O	BF	2900		CFM/%L	OUTFLOW FWD
O	BA	2900		CFM/%L	OUTFLOW AFT
O	LCF	.068		%(DEC)	LENGTH CLOUD FWD
O	LCA	.068		%(DEC)	LENGTH CLOUD AFT
O	LC	.387		%(DEC)	LENGTH OF CLOUD
O	LSF	.612		%(DEC)	LENGTH SMOKE FREE

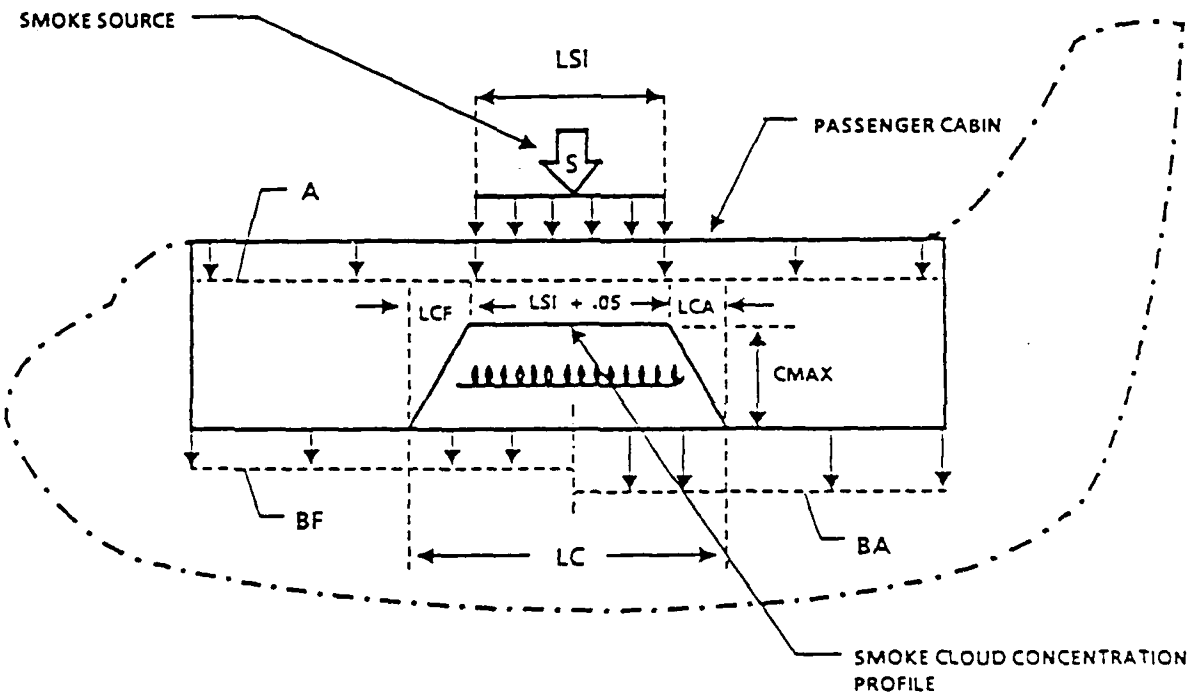


FIGURE 5-1. SCENARIO 1

```
=============================== Equation Sheet ======================
 St Equation
 -- --------
    A+S=(BF+BA)/2
    R=BA/BF
    CMAX=CIN*S/(S+A*(LSI+.05))
    S*CIN=(.5*LCF*BA*CMAX)+(LSI+.05)*BA*CMAX+(.5*LCA*BA*CMAX)
    R=LCA/LCF
    LC=LCF+(LSI+.05)+LCA
    LSF=1-LC
=============================== Variable Sheet ======================
```

St	Name	Value	Dsp Unit	Cal Unit	Comments
I	S	200		CFM	SMOKE INFLOW
I	CIN	.00045		LB/CU.FT	SMK CONCEN IN
I	LSI	0		%(DEC)	LENGTH SMOKE IN
I	A	2700		CFM	AIR INFLOW
I	R	2		-	BALANCE RATIO
O	CMAX	.000268		LB/CU.FT	SMK CONCEN MAX
O	BF	1933.3		CFM/%L	OUTFLOW FWD
O	BA	3866.6		CFM/%L	OUTFLOW AFT
O	LCF	.024		%(DEC)	LENGTH CLOUD FWD
O	LCA	.048		%(DEC)	LENGTH CLOUD AFT
O	LC	.123		%(DEC)	LENGTH OF CLOUD
O	LSF	.876		%(DEC)	LENGTH SMOKE FREE

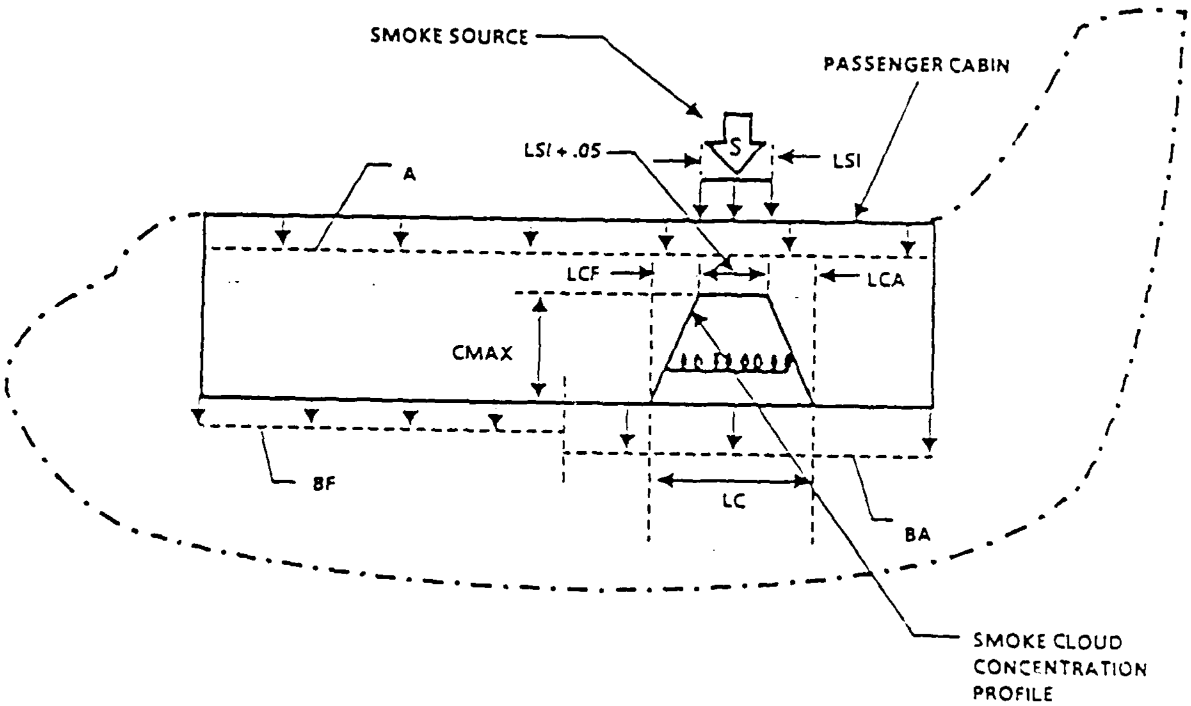


FIGURE 5-2. SCENARIO 2

```
================================ Equation Sheet ======================
St Equation
-- --------
*  A+S=(BF+BA)/2
*  R=BA/BF
*  CMAX=CIN*S/(S+A*(LSI+.05))
*  S*CIN=(.5*LCF*BA*CMAX)+(LSI+.05)*BA*CMAX
*  LC=LCF+(LSI+.05)
*  LSF=1-LC
================================ Variable Sheet ======================
St Name          Value          Dsp Unit  Cal Unit  Comments
-- ----          -----          --------  --------  --------
I  S             200                      CFM       SMOKE INFLOW
I  CIN           .00045                   LB/CU.FT  SMK CONCEN IN
I  LSI           0                        %(DEC)    LENGTH SMOKE IN
I  A             1760                     CFM       AIR INFLOW
I  R             1.67                     -         BALANCE RATIO
O  CMAX          .000312                  LB/CU.FT  SMK CONCEN MAX
O  BA            2451.8                   CFM/%L    OUTFLOW AFT
O  BF            1468.1                   CFM/%L    OUTFLOW FWD
O  LCF           .134                     %(DEC)    LENGTH CLOUD FWD
O  LC            .184                     %(DEC)    LENGTH OF CLOUD
O  LSF           .815                     %(DEC)    LENGTH SMOKE FREE
```

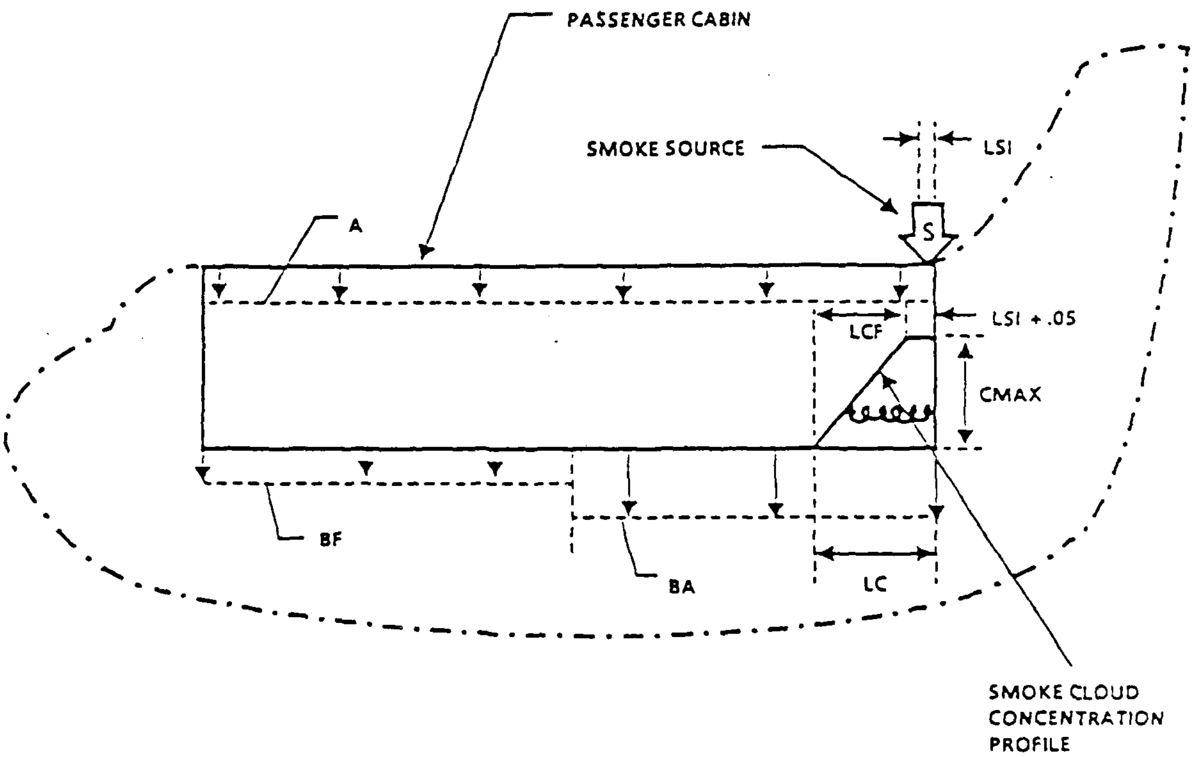


FIGURE 5-3. SCENARIO 3

```
=================================== Equation Sheet ========================
St Equation
-- --------
   A+S=(BF+BA)/2
   R=BA/BF
   CMAX=CIN*S/(S+A*(LSI+.05))
   S*CIN=(LSI+.05)*BF*CMAX+(.5*LCA*BF*CMAX)
   LC=(LSI+.05)+LCA
   LSF=1-LC
=================================== Variable Sheet ========================
```

St	Name	Value	Dsp Unit	Cal Unit	Comments
I	S	200		CFM	SMOKE INFLOW
I	CIN	.00045		LB/CU.FT	SMK CONCEN IN
I	LSI	0		%(DEC)	LENGTH SMOKE IN
I	A	7161		CFM	AIR INFLOW
I	R	1		-	BALANCE RATIO
O	CMAX	.000161		LB/CU.FT	SMK CONCEN MAX
O	BF	7361		CFM/%L	OUTFLOW FWD
O	BA	7361		CFM/%L	OUTFLOW AFT
O	LCA	.051		%(DEC)	LENGTH CLOUD AFT
O	LC	.101		%(DEC)	LENGTH OF CLOUD
O	LSF	.898		%(DEC)	LENGTH SMOKE FREE

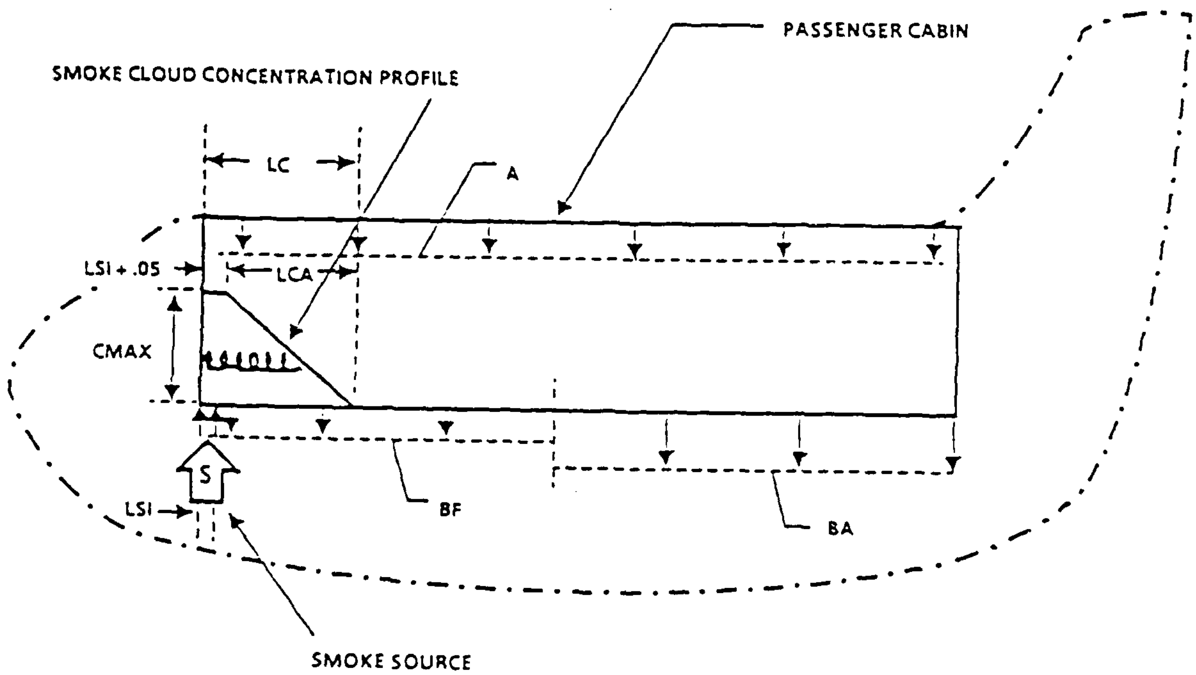
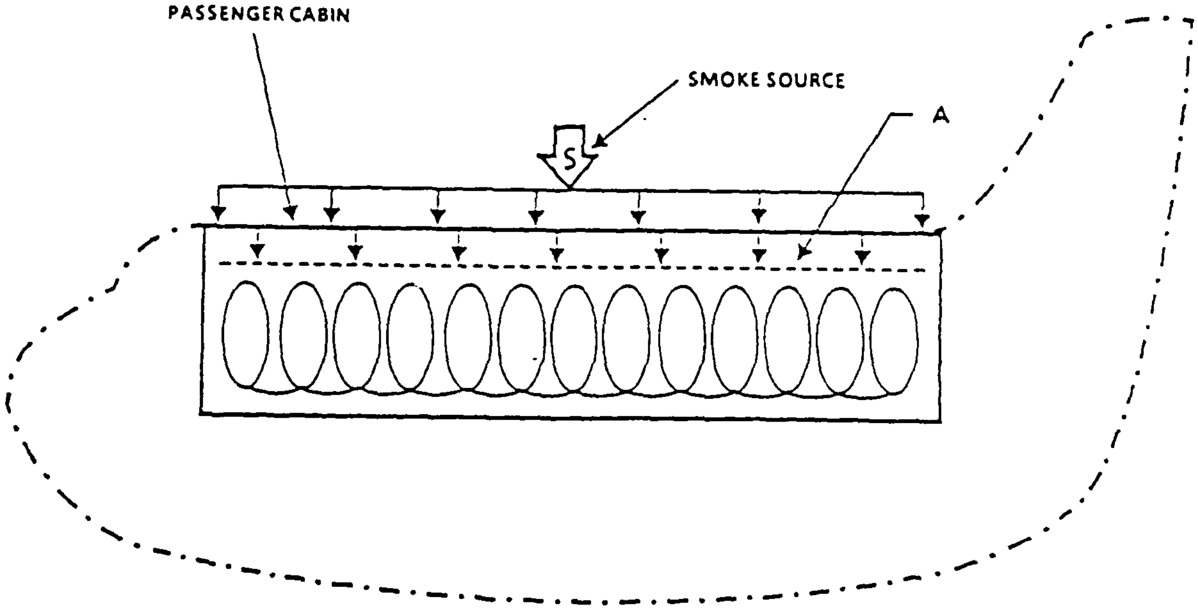


FIGURE 5-4. SCENARIO 4

```
================================ Equation Sheet ======================
St Equation
-- --------
   CMAX=CIN*S/(A+S)
   LSF=0
================================ Variable Sheet ======================
St Name           Value            Dsp Unit  Cal Unit   Comments
-- ----           -----            --------  --------   --------
I  S              200                        CFM        SMOKE INFLOW
I  CIN            .00045                     LB/CU.FT   SMK CONCEN IN
I  A              2700                       CFM        AIR INFLOW
O  CMAX           .000031                    LB/CU.FT   SMK CONCEN MAX
O  LSF            0                          %(DEC)     LENGTH SMOKE FREE
```



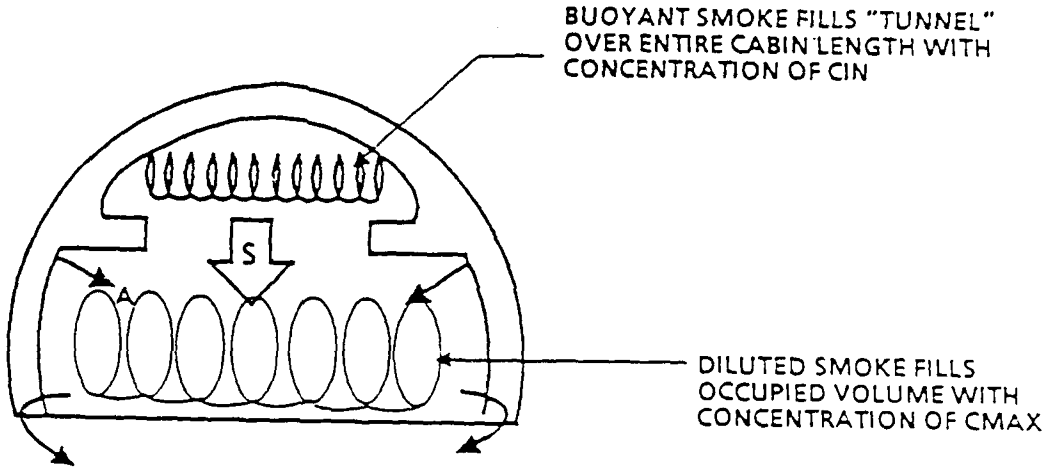


FIGURE 5-5. EQUATION SET No. 5

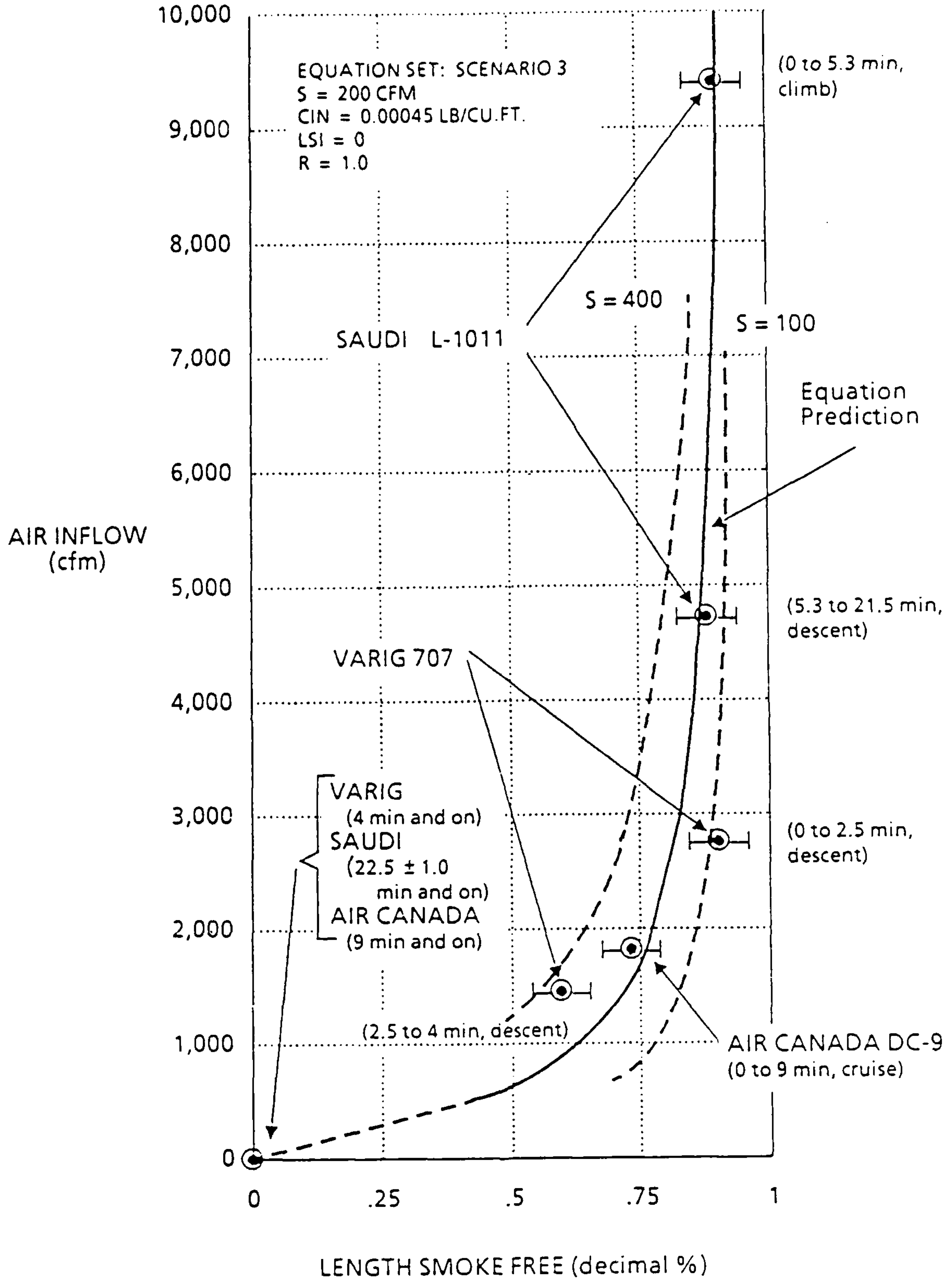


FIGURE 5-6. EQUATIONS COMPARED TO PAST FIRES

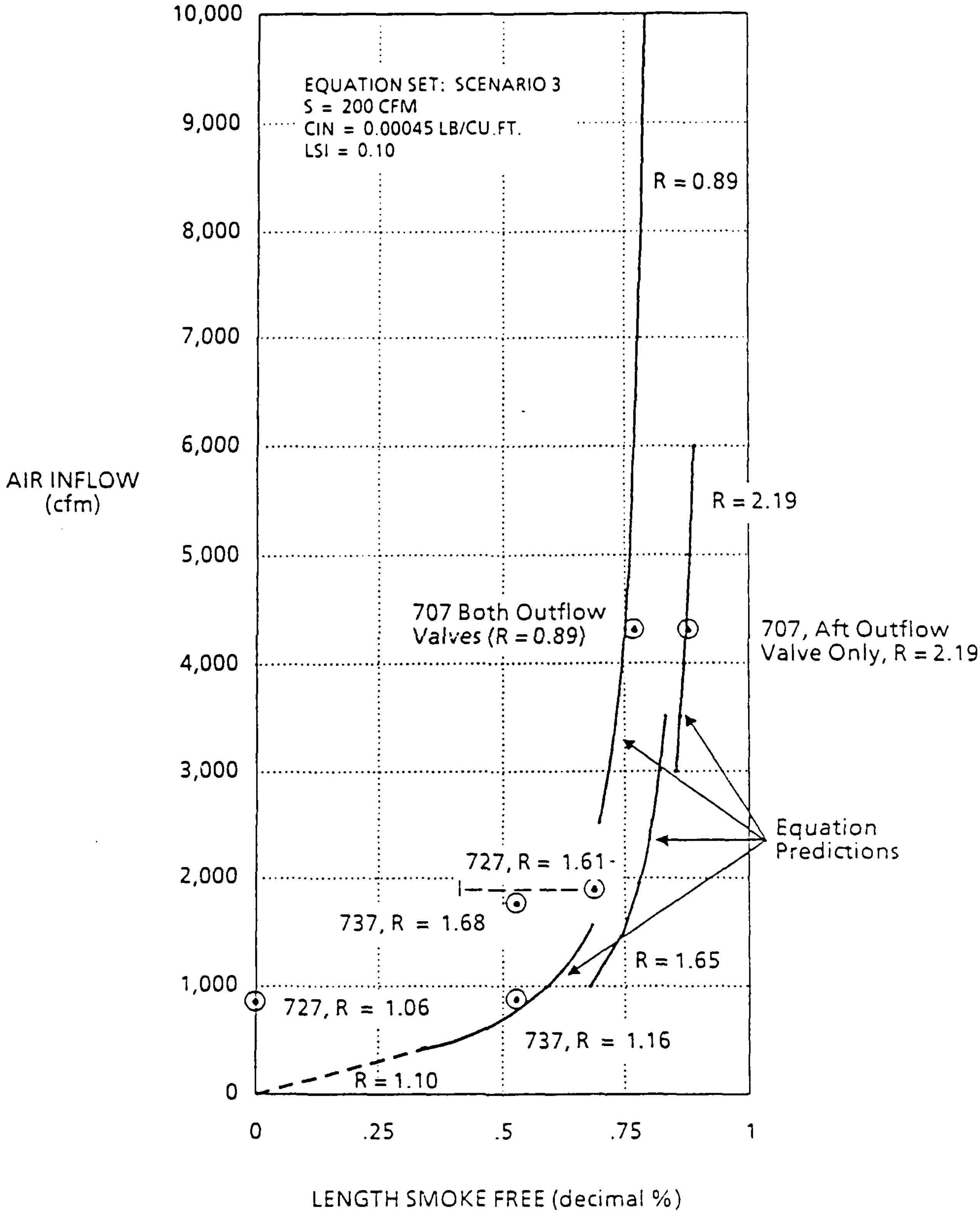


FIGURE 5-7. EQUATIONS COMPARED TO TESTS

6. EFFECTIVENESS ANALYSES OF CURRENT AIRPLANES AND THE ENHANCEMENT CONCEPTS

6.1 GENERAL

Using the equations described in Section 5, the smoke venting effectiveness has been analyzed for each of the Boeing, Douglas and Lockheed airplanes covered by this study in its current configuration and in both the Concept A and Concept B configurations as described in Section 4 to predict the effectiveness during each of the four fire/smoke scenarios presented in Section 3. The analysis results are tabulated on Figure 6-1.

Most of the air inflow rates, A, listed in the figure for the current configurations are taken from DOT/FAA/CT-86/41-I[12]. The exception is the flows for the Boeing 707 which are taken from D6-3097[13].

For current configurations, the flows are based on the assumption that each airplane uses the current emergency procedure for passenger cabin smoke evacuation. The beginning and end of each scenario were analyzed during cruise at altitude of 35,000 ft (35K) and ground operation at sea level (SL).

For the Concept A and Concept B configurations, the flows are taken from the concept descriptions in Section 4. It is assumed that all recirculation fans will be turned off during these scenarios. Also, the outflow valve(s) will be used in the combinations shown on Figure 6-2 and thus provide the balance ratios R as listed on Figure 6-1. The listed R values were determined by calculating the changes to the current airplane flow balance caused by the increased ventilation inflow, changed outflow valve locations, recirculation shutdown, leakage and any major overboard dump flows. The current airplane flow balances in normal cruise were assumed to be R = 1.0 for 707 and L-1011 airplanes with both forward and aft outflow valves, R = 1.0 for Douglas airplanes with balancing restrictors in the cabin outlet grilles and R = 1.67 for Boeing airplanes with aft outflow valve(s) and unrestricted cabin outlet grilles. The calculated R values are considered to be accurate within about 15%.

6.2 COMPARISON OF ANALYSIS RESULTS

A review of Figure 6-1 shows that all of the results can be compared in certain groups in which all of the values are within relatively narrow ranges and thus can be averaged. The groupings for this comparison are shown on Figure 6-3 which presents the values determined by averaging the results from all airplanes. The figure omits the CMAX averages for equation sets 1 thru 4 because the concentrations within the smoke cloud are unacceptably high and thus only the LSF averages are significant. For equation set 5, the figure omits the LSF values because the smoke cloud extends throughout the passenger cabin and thus only the CMAX averages are significant.

6.2.1 EFFECTIVENESS OF CONCEPT A

As shown on Figures 6-1 and 6-3, Concept A would provide slightly improved smoke venting compared to the current airplane configurations during certain operating phases. During cruise operation and ground operation with engines ON, the average improvements in LSF are relatively small due to the high LSF on current airplanes and the inherent limits on increasing the ventilation airflow rates and utilizing the effect of the additional outflow valve.

---

[12] FAA Report No. DOT/FAA/CT-86/41-I, "Aircraft Ventilation Systems Study, Volume I", dated Sept. 1986.

[13] Boeing Document D6-3097, "Estimated Performance and Operation of Engine Bleed System for Air Conditioning", dated 2/10/59.

Similarly, during cruise operation and ground operation with engines ON, the average improvements in CMAX are relatively small due to the low CMAX on current airplanes and the inherent limits on increasing the ventilation airflow.

The complete lack of improvement during ground operation with engines OFF was expected because Concept A includes no feature to provide smoke venting during engine OFF operation.

6.2.2 EFFECTIVENESS OF CONCEPT B

As shown on Figures 6-1 and 6-3, Concept B would provide improved smoke venting compared to the current airplane configurations during certain operating phases. During cruise operation the improvements in average LSF are relatively small due to (1) the high LSF on current airplanes, (2) the fact that Concept B does not increase ventilation airflow in cruise and (3) the inherent limits on utilizing the effect of the added dump valve. There would be no improvement in CMAX because Concept B during cruise does not increase ventilation airflow which is the only feature that influences CMAX.

During ground operation with engines ON, the improvements in average LSF are relatively small due to the high LSF on current airplanes and the inherent limits on increasing ventilation with ram air systems and utilizing the effect of the added dump valve. The improvements in average CMAX are relatively small due to the low CMAX on current airplanes and the inherent limit on increasing ventilation with ram air systems.

During ground operation with engines OFF, Concept B would provide large improvements in both LSF average and CMAX averages because the current airplanes have no smoke venting capability when engines are OFF.

AIRPLANE Configuration: Altitude & A (cfm)		Effectiveness Analysis Results										
		Scenario 1			Scenarios 2 and 3					Scenario 4		
		Equation Set 1			Equation Set 2 & 3			Equation Set 5		Equation Set 4		
		R	CMAX	LSF	R	CMAX	LSF	CMAX	LSF	R	CMAX	LSF
707												
Current:												
35K	4050	1.0	7	.66	1.0	22	.86	2	0	1.0	22	.86
SL (eng's ON)	4050	.88	7	.66	.88	22	.85	2	0	.88	22	.87
SL (eng's OFF)	-0-	--	45	0	--	45	0	45	0	--	45	0
Concept A:												
35K	4050	2.77	7	.67	2.77	22	.92	2	0	.36	22	.92
SL (eng's ON)	4050	2.37	7	.67	2.37	22	.92	2	0	.20	22	.94
SL (eng's OFF)	-0-	--	45	0	--	45	0	45	0	--	45	0
Concept B:												
35K	4050	2.77	7	.67	2.77	22	.92	2	0	.36	22	.92
SL (eng's ON)	4050	2.37	7	.67	2.37	22	.92	2	0	.20	22	.94
SL (eng's OFF)	2160	1.49	12	.59	1.49	29	.83	4	0	.20	29	.89
727-100												
Current:												
35K	2126	1.67	12	.59	1.67	29	.84			1.67	29	.70
SL (eng's ON)	N/A											
SL (eng's OFF)	-0-	--	45	0	--	45	0			--	45	0
Concept A:												
35K	2126	1.67	12	.59	1.67	29	.84	N/A		.60	29	.84
SL (eng's ON)	N/A											
SL (eng's OFF)	-0-	--	45	0	--	45	0			--	45	0
Concept B:												
35K	2126	1.67	12	.59	1.67	29	.84			.60	29	.84
SL (eng's ON)	N/A											
SL (eng's OFF)	1647	1.06	15	.53	1.06	32	.75			.45	32	.83

A = Air inflow volumetric flow rate (cfm)
R = Outflow balance ratio (unitless)
CMAX = Maximum concentration of the smoke cloud in the occupied cabin volume (0.00001 lb/cu ft)
LSF = Length of the cabin that is smoke-free (decimal percent of cabin length)
35K = 35,000 ft. altitude
SL (eng's ON) = Sea Level with engines operating
SL (eng's OFF) = Sea Level with engines not operating

FIGURE 6-1. (SHEET 1 of 6) EFFECTIVENESS ANALYSIS RESULTS

AIRPLANE Configuration: Altitude & A (cfm)		Effectiveness Analysis Results										
		Scenario 1			Scenarios 2 and 3					Scenario 4		
		Equation Set 1			Equation Set 2 & 3			Equation Set 5		Equation Set 4		
		R	CMAX	LSF	R	CMAX	LSF	CMAX	LSF	R	CMAX	LSF
727-200												
Current:												
35K	2850	1.67	10	.63	1.67	26	.87			1.67	26	.75
SL (eng's ON)	2386	1.25	11	.60	1.25	28	.83			1.25	28	.77
SL (eng's OFF)	-0-	--	45	0	--	45	0			--	45	0
Concept A:												
35K	3278	1.74	9	.64	1.74	25	.89	N/A		.57	25	.89
SL (eng's ON)	2744	1.33	10	.62	1.33	27	.85			.45	27	.88
SL (eng's OFF)	-0-	--	45	0	--	45	0			--	45	0
Concept B:												
35K	2850	1.67	10	.63	1.67	26	.87			.60	26	.87
SL (eng's ON)	2386	1.25	11	.60	1.25	28	.83			.45	28	.87
SL (eng's OFF)	1647	1.06	15	.53	1.06	32	.75			.45	32	.83
737-100/200												
Current:												
35K	1778	1.67	14	.56	1.67	31	.82			1.67	31	.66
SL (eng's ON)	1840	1.11	14	.55	1.11	31	.78			1.11	31	.75
SL (eng's OFF)	-0-	--	45	0	--	45	0			--	45	0
Concept A:												
35K	2667	1.86	10	.62	1.86	27	.87	N/A		.54	27	.87
SL (eng's ON)	2760	1.33	10	.62	1.33	27	.85			.45	27	.88
SL (eng's OFF)	-0-	--	45	0	--	45	0			--	45	0
Concept B:												
35K	1778	1.67	14	.56	1.67	31	.82			1.67	31	.66
SL (eng's ON)	1840	(use engines OFF)										
SL (eng's OFF)	2284	1.22	12	.59	1.22	29	.82			.45	29	.87

A = Air inflow volumetric flow rate (cfm)
R = Outflow balance ratio (unitless)
CMAX = Maximum concentration of the smoke cloud in the occupied cabin volume (0.00001 lb/cu ft)
LSF = Length of the cabin that is smoke-free (decimal percent of cabin length)
35K = 35,000 ft. altitude
SL (eng's ON) = Sea Level with engines operating
SL (eng's OFF) = Sea Level with engines not operating

FIGURE 6-1. (SHEET 2 of 6) EFFECTIVENESS ANALYSIS RESULTS

AIRPLANE Configuration: Altitude & A (cfm)		Effectiveness Analysis Results: Scenario 1 — Equation Set 1 R	CMAX	LSF	Scenarios 2 and 3 — Equation Set 2 & 3 R	CMAX	LSF	Scenarios 2 and 3 — Equation Set 5 CMAX	LSF	Scenario 4 — Equation Set 4 R	CMAX	LSF
737-300												
Current:												
35K	1760	1.67	14	.56	1.67	31	.82	N/A		1.67	31	.66
SL (eng's ON)	1940	1.13	13	.56	1.13	30	.79	N/A		1.13	30	.75
SL (eng's OFF)	-0-	--	45	0	--	45	0	N/A		--	45	0
Concept A:												
35K	2640	1.86	10	.62	1.86	27	.87	N/A		.54	27	.87
SL (eng's ON)	2910	1.36	10	.62	1.36	26	.86	N/A		.45	26	.89
SL (eng's OFF)	-0-	--	45	0	--	45	0	N/A		--	45	0
Concept B:												
35K	1760	1.67	14	.56	1.67	31	.82	N/A		1.67	31	.66
SL (eng's ON)	1940	(use engines OFF)										
SL (eng's OFF)	2284	1.22	12	.59	1.22	29	.82	N/A		.45	29	.87
747												
Current:												
35K	6692	1.67	5	.70	1.67	17	.93	1	0	1.67	17	.84
SL (eng's ON)	7818	1.46	4	.70	1.46	15	.93	1	0	1.46	15	.87
SL (eng's OFF)	-0-	--	45	0	--	45	0	45	0	--	45	0
Concept A:												
35K	6692	1.67	5	.70	1.67	17	.93	1	0	.60	17	.93
SL (eng's ON)	7818	1.46	4	.70	1.46	15	.93	1	0	.97	15	.90
SL (eng's OFF)	-0-	--	45	0	--	45	0	45	0	--	45	0
Concept B:												
35K	6692	1.67	5	.70	1.67	17	.93	1	0	.60	17	.93
SL (eng's ON)	7818	1.46	4	.70	1.46	15	.93	1	0	.97	15	.90
SL (eng's OFF)	7476	1.44	4	.70	1.44	16	.92	1	0	.97	16	.90

A = Air inflow volumetric flow rate (cfm)
R = Outflow balance ratio (unitless)
CMAX = Maximum concentration of the smoke cloud in the occupied cabin volume (0.00001 lb/cu ft)
LSF = Length of the cabin that is smoke-free (decimal percent of cabin length)
35K = 35,000 ft. altitude
SL (eng's ON) = Sea Level with engines operating
SL (eng's OFF) = Sea Level with engines not operating

FIGURE 6-1. (SHEET 3 of 6) EFFECTIVENESS ANALYSIS RESULTS

AIRPLANE Configuration: Altitude & A (cfm)		Effectiveness Analysis Results										
		Scenario 1			Scenarios 2 and 3					Scenario 4		
		Equation Set 1			Equation Set 2 & 3			Equation Set 5		Equation Set 4		
		R	CMAX	LSF	R	CMAX	LSF	CMAX	LSF	R	CMAX	LSF
757												
Current:												
35K	2756	1.19	10	.62	1.19	27	.84			1.19	27	.80
SL (eng's ON)	2838	1.34	10	.62	1.34	26	.85			1.34	26	.79
SL (eng's OFF)	-0-	--	45	0	--	45	0			--	45	0
Concept A:												
35K	3583	1.37	8	.65	1.37	24	.88	N/A		.56	24	.89
SL (eng's ON)	3689	1.48	8	.65	1.48	23	.88			.45	23	.91
SL (eng's OFF)	-0-	--	45	0	--	45	0			--	45	0
Concept B:												
35K	2756	1.19	10	.62	1.19	27	.84			1.19	27	.80
SL (eng's ON)	2838	(use engines OFF)										
SL (eng's OFF)	3313	1.43	9	.64	1.43	25	.87			.45	25	.90
767												
Current:												
35K	3228	1.67	9	.64	1.67	25	.88			1.67	25	.77
SL (eng's ON)	3162	2.24	9	.64	2.24	25	.90			2.24	25	.70
SL (eng's OFF)	-0-	--	45	0	--	45	0			--	45	0
Concept A:												
35K	3228	1.67	9	.64	1.67	25	.88	N/A		.60	25	.88
SL (eng's ON)	3162	2.24	9	.64	2.24	25	.90			.45	25	.90
SL (eng's OFF)	-0-	--	45	0	--	45	0			--	45	0
Concept B:												
35K	3228	1.67	9	.64	1.67	25	.88			.60	25	.88
SL (eng's ON)	3162	(use engines OFF)										
SL (eng's OFF)	4432	2.24	7	.67	2.24	21	.92			.45	21	.92

A = Air inflow volumetric flow rate (cfm)
R = Outflow balance ratio (unitless)
CMAX = Maximum concentration of the smoke cloud in the occupied cabin volume (0.00001 lb/cu ft)
LSF = Length of the cabin that is smoke-free (decimal percent of cabin length)
35K = 35,000 ft. altitude
SL (eng's ON) = Sea Level with engines operating
SL (eng's OFF) = Sea Level with engines not operating

FIGURE 6-1. (SHEET 4 of 6) EFFECTIVENESS ANALYSIS RESULTS

AIRPLANE Configuration: Altitude & A (cfm)		Effectiveness Analysis Results										
		Scenario 1			Scenarios 2 and 3					Scenario 4		
		Equation Set 1			Equation Set 2 & 3			Equation Set 5		Equation Set 4		
		R	CMAX	LSF	R	CMAX	LSF	CMAX	LSF	R	CMAX	LSF
DC-8-71/72/73												
Current:												
35K	2862	1.0	10	.62	1.0	26	.83	3	0	1.0	26	.83
SL (eng's ON)	2750	1.24	10	.62	1.24	27	.84	3	0	1.24	27	.79
SL (eng's OFF)	-0-	--	45	0	--	45	0	45	0	--	45	0
Concept A:												
35K	3578	1.05	8	.64	1.05	24	.85	2	0	.30	24	.92
SL (eng's ON)	3438	1.24	8	.64	1.24	24	.87	2	0	.19	24	.93
SL (eng's OFF)	-0-	--	45	0	--	45	0	45	0	--	45	0
Concept B:												
35K	2862	1.0	10	.62	1.0	26	.83	3	0	1.0	26	.83
SL (eng's ON)	2750	1.24	10	.62	1.24	27	.84	3	0	.19	27	.91
SL (eng's OFF)	1756	1.24	14	.55	1.24	31	.78	5	0	.19	31	.87
DC-9-30/40/50												
Current:												
35K	1769	1.0	14	.55	1.0	31	.76	5	0	1.0	31	.76
SL (eng's ON)	971	1.24	20	.41	1.24	36	.63	8	0	1.24	36	.57
SL (eng's OFF)	-0-	--	45	0	--	45	0	45	0	--	45	0
Concept A:												
35K	1875	1.01	13	.56	1.01	31	.77	4	0	.45	31	.84
SL (eng's ON)	1029	1.24	20	.43	1.24	36	.68	7	0	.37	36	.77
SL (eng's OFF)	-0-	--	45	0	--	45	0	45	0	--	45	0
Concept B:												
35K	1769	1.0	14	.55	1.0	31	.76	5	0	1.0	31	.76
SL (eng's ON)	971	(use engines OFF)										
SL (eng's OFF)	1747	1.24	14	.55	1.24	31	.78	5	0	.37	31	.85

A = Air inflow volumetric flow rate (cfm)
R = Outflow balance ratio (unitless)
CMAX = Maximum concentration of the smoke cloud in the occupied cabin volume 0.00001 lb/cu ft)
LSF = Length of the cabin that is smoke-free (decimal percent of cabin length)
35K = 35,000 ft. altitude
SL (eng's ON) = Sea Level with engines operating
SL (eng's OFF) = Sea Level with engines not operating

FIGURE 6-1. (SHEET 5 of 6) EFFECTIVENESS ANALYSIS RESULTS

AIRPLANE Configuration: Altitude & A (cfm)		Effectiveness Analysis Results: Scenario 1, Equation Set 1			Scenarios 2 and 3, Equation Set 2 & 3			Scenarios 2 and 3, Equation Set 5		Scenario 4, Equation Set 4		
		R	CMAX	LSF	R	CMAX	LSF	CMAX	LSF	R	CMAX	LSF
DC-10												
Current:												
35K	5717	1.0	6	.68	1.0	19	.89			1.0	19	.89
SL (eng's ON)	5310	.81	6	.68	.81	19	.86			.81	19	.90
SL (eng's OFF)	-0-	--	45	0	--	45	0			--	45	0
Concept A:												
35K	6575	1.95	5	.70	1.95	17	.93	N/A		.97	17	.90
SL (eng's ON)	6107	2.70	5	.70	2.70	18	.94			.81	18	.90
SL (eng's OFF)	-0-	--	45	0	--	45	0			--	45	0
Concept B:												
35K	5717	1.0	6	.68	1.0	19	.89			1.0	19	.89
SL (eng's ON)	5310	(use engines OFF)										
SL (eng's OFF)	5465	2.70	6	.69	2.70	19	.94			.81	19	.89
L-1011												
Current:												
35K	5381	1.0	6	.68	1.0	19	.88			1.0	19	.88
SL (eng's ON)	5606	.95	6	.68	.95	19	.88			.95	19	.39
SL (eng's OFF)	-0-	--	45	0	--	45	0			--	45	0
Concept A:												
35K	8072	1.86	4	.71	1.86	15	.94	N/A		.54	15	.94
SL (eng's ON)	8409	1.69	4	.71	1.69	15	.94			.45	15	.95
SL (eng's OFF)	-0-	--	45	0	--	45	0			--	45	0
Concept B:												
35K	5381	1.67	6	.68	1.67	19	.92			.60	19	.92
SL (eng's ON)	5606	(use engines OFF)										
SL (eng's OFF)	8409	1.69	4	.71	1.69	15	.94			.45	15	.95

A = Air inflow volumetric flow rate (cfm)
R = Outflow balance ratio (unitless)
CMAX = Maximum concentration of the smoke cloud in the occupied cabin volume (0.00001 lb/cu ft)
LSF = Length of the cabin that is smoke-free (decimal percent of cabin length)
35K = 35,000 ft. altitude
SL (eng's ON) = Sea Level with engines operating
SL (eng's OFF) = Sea Level with engines not operating

FIGURE 6-1. (SHEET 6 of 6) EFFECTIVENESS ANALYSIS RESULTS

<table>
<tr><th rowspan="2">AIRPLANE MODEL(S)</th><th colspan="2">CONFIGURATIONS</th><th colspan="2">FIRE LOCATION</th><th rowspan="2">OUTFLOW VALVE(S) USED</th></tr>
<tr><th>CURRENT</th><th>CONCEPTS A & B</th><th>FWD (Scenario 4)</th><th>AFT (Scenarios 1, 2 & 3)</th></tr>
<tr><td rowspan="3">707
L-1011</td><td>●</td><td></td><td colspan="2">●</td><td>1 FWD + 1AFT</td></tr>
<tr><td rowspan="2"></td><td rowspan="2">●</td><td>●</td><td></td><td>1 FWD</td></tr>
<tr><td></td><td>●</td><td>1 AFT</td></tr>
<tr><td rowspan="3">727-100</td><td>●</td><td></td><td colspan="2">●</td><td>2 AFT</td></tr>
<tr><td rowspan="2"></td><td rowspan="2">●</td><td>●</td><td></td><td>1 FWD (NEW)</td></tr>
<tr><td></td><td>●</td><td>2 AFT</td></tr>
<tr><td rowspan="3">727-200,
737, 757, 767,
DC-8, DC-9</td><td>●</td><td></td><td colspan="2">●</td><td>1 AFT</td></tr>
<tr><td rowspan="2"></td><td rowspan="2">●</td><td>●</td><td></td><td>1.FWD (NEW)</td></tr>
<tr><td></td><td>●</td><td>1 AFT</td></tr>
<tr><td rowspan="4">747</td><td>●</td><td></td><td colspan="2">●</td><td>2 AFT</td></tr>
<tr><td rowspan="3"></td><td rowspan="3">●</td><td>● (FLIGHT)</td><td></td><td>1 FWD (NEW)</td></tr>
<tr><td>● (LANDING)</td><td></td><td>1 FWD (NEW) + 1AFT</td></tr>
<tr><td></td><td>●</td><td>2 AFT</td></tr>
<tr><td rowspan="3">DC-10</td><td>●</td><td></td><td colspan="2">●</td><td>1 FWD</td></tr>
<tr><td rowspan="2"></td><td rowspan="2">●</td><td>●</td><td></td><td>1 FWD</td></tr>
<tr><td></td><td>●</td><td>1 AFT (NEW)</td></tr>
</table>

FIGURE 6-2. OUTFLOW VALVE USAGE SCHEDULE

	AVERAGE LSF (DECIMAL PERCENT) EQUATION SETS 1 THRU 4			AVERAGE CMAX (0.00001 lb/cu ft) EQUATION SET 5		
	CURRENT CONFIGURATION	CONCEPT A	CONCEPT B	CURRENT CONFIGURATION	CONCEPT A	CONCEPT B
CRUISE AT 35,000 FT.	.778	.825	.794	2.75	2.25	2.75
SEA LEVEL WITH ENGINES ON	.765	.820	.828	3.50	3.00	2.00
SEA LEVEL WITH ENGINES OFF	-0-	-0-	.795	45	45	3.75

LSF = Length of the cabin that is smoke-free (decimal percent of cabin length)

CMAX = Maximum concentration of the smoke cloud in the occupied cabin volume (0.00001 lb/cu ft)

FIGURE 6-3. COMPARISON OF AVERAGED ANALYSIS RESULTS

7. COST/EFFECTIVENESS COMPARISON

Figures 7-1 and 7-2 present a comparison of the estimated incorporation costs and the analytically predicted smoke venting effectiveness of Concepts A and B. The incorporation costs shown are the total of all the estimates given in Section 4 and the effectiveness averages are from Section 6.

Ccmparing Concept A and the current airplanes by considering the bar graphs on Figure 7-1 shows that Concept A would provide only small improvements in LSF and CMAX. The 4.7% to 5.5 % increase in LSF is considered only slightly significant because the current airplanes maintain more than 75% of the cabin smoke-free and the passengers could probably avoid the smoke cloud with considerably less smoke-free cabin length. Similarly, the decrease in CMAX is only slightly significant in view of the fact that a smoke concentration of 0.000035 lb/cu ft corresponds to a relatively safe light transmissivity of 73% over a 1-foot path. It is concluded that Concept A would provide slightly significant smoke venting improvement compared to current airplanes.

Comparing Concept B and the current airplanes by considering the bar graphs on Figures 7-1 shows that Concept B would provide only small improvements in LSF and CMAX during cruise and sea level operation with engines ON. These improvements are considered slightly significant for the same reasons as stated above for Concept A. During sea level operation with engines OFF, Concept B would provide large improvements in LSF and CMAX. These improvements would be of limited significance because they would prevail only during the approximately 2 minute time period assumed for passenger evacuation. Past fires as described in Section 2.5 have indicated that passengers have survived smoke conditions without ventilation for longer than 2 minutes. For example, in the Varig 707 fire (see Paragraph 2.5.1) after about 1.5 minutes with reduced ventilation and during the next 2.5 minutes with no ventilation prior to the crash landing, some passengers were reported to have fainted; out of the 125 people reported to be in the passenger cabin, there were 3 survivors one of which was rescued by firemen who arrived at the scene about 8 minutes after the crash landing. For another example, in the Air Canada DC-9 fire (see Paragraph 2.5.3) 48% of the passenger cabin occupants survived even though the cabin was unventilated for about 11 minutes from top-of-descent until touchdown plus 1 to 2 minutes to stop the airplane and evacuate passengers. This past fire experience in current airplanes (without Concept B) shows that the smoke cloud spreading after ventilation shutoff is slow enough to allow successful passenger evacuation if the engine shutoff occurs just before the evacuation begins. It is concluded that Concept B would provide slightly significant smoke venting improvement compared to current airplanes during cruise and sea level (ground) operation with engines ON and limited significance improvement during sea level (ground) operation with engines OFF.

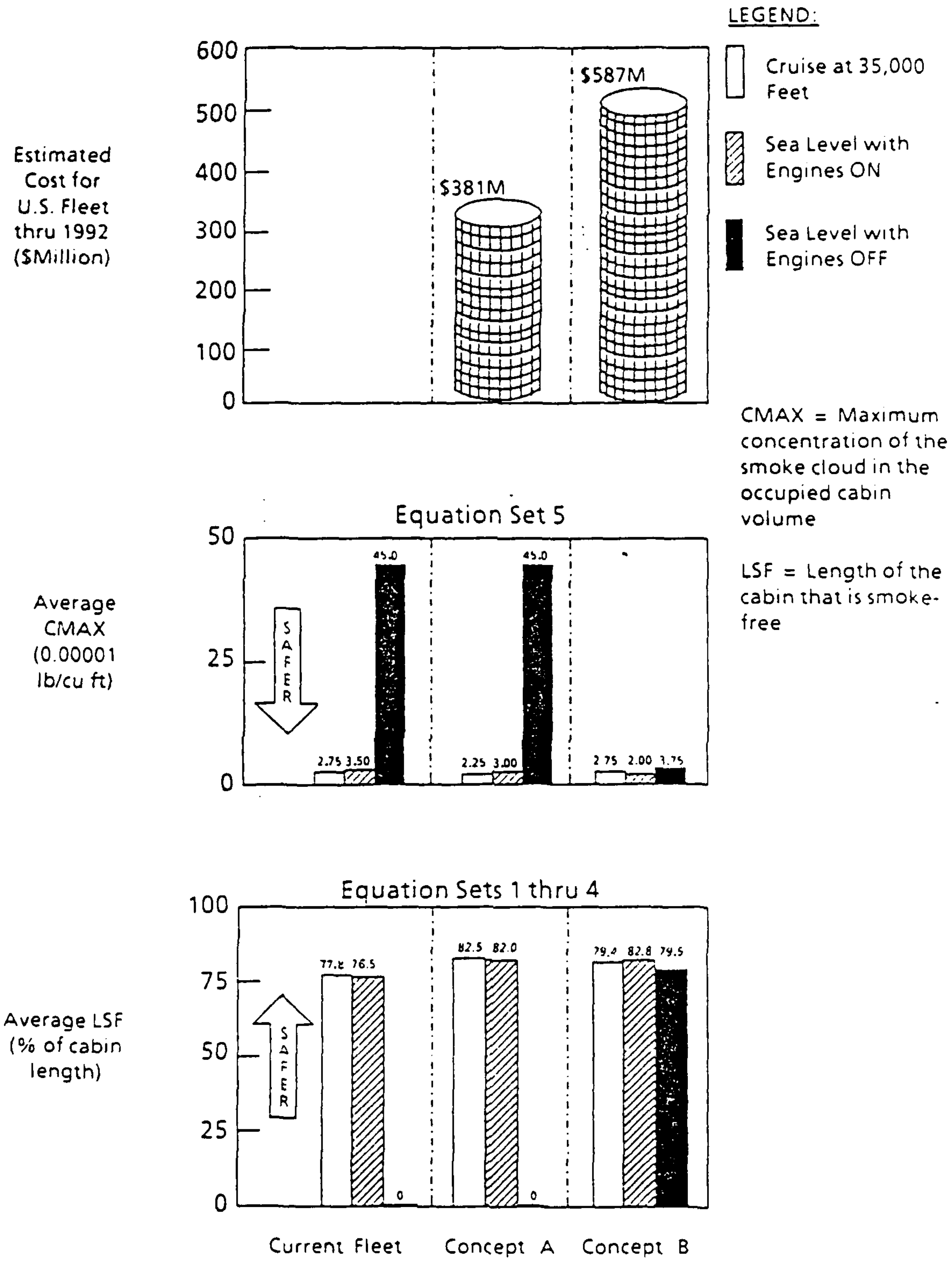


FIGURE 7-1. COST/EFFECTIVENESS COMPARISON

Airplane Models	Number of Airplanes			Concept A		Concept B	
	Current U.S. Fleet	Production Thru 1992	Total	High Flow %	Cost Estimate $ Millions	Ram Vent %	Cost Estimate $ Millions
707	36	0	36	145	1.9	77	2.0
727-100	344	0	344	100	9.9	77	14.2
727-200	853	0	853	115	26.2	69	30.8
737	641	727	1,368	150	37.9	124/118c	54.3
747	167	226	393	100	8.1	96	35.6
757	98	187	285	130	9.5	117	15.5
767	87	212	299	100	6.1	140	15.8
DC-8	188	0	188	125	22.7	63	38.5
DC-9/MD-80	699	502	1,201	106	165.7	180	244.8
DC-10	190	200	390	115	69.7	103	100.6
L-1011	117	0	117	150a	7.8 b	150a	12.1 b
Airbus	65	160	225	150a	15.0 b	150a	23.2 b
Totals	3,485	2,214	5,699	–	380.5	–	587.4

a = assumed
b = based on average from rest of fleet
c – for 737-100/200 and 737-300, respectively

FIGURE 7-2. AIRPLANE/CONCEPT/COST SUMMARY

8. CONCLUSIONS

8.1 DATA SYNOPSIS: There are no current Federal Aviation Regulations that include specific requirements for the venting of continuously generated smoke from passenger cabins during inflight fires. Related smoke data concerning other situations, such as non-continuously generated smoke in the cockpit, is included in some Advisory Circulars, correspondence, test standards and past certification test reports.

8.2 EMERGENCY PROCEDURES: Although not required by the Federal Aviation Regulations, all of the Operations Manuals prepared by the manufacturers for Boeing, Douglas and Lockheed airplanes have emergency procedures for venting smoke from passenger cabins.

8.3 CONCEPT COSTS: The two concepts that were studied during this contract for enhanced smoke venting from passenger cabins during inflight fires are, at least partially, feasible for all of the large, passenger airplanes in the U.S. fleet:

- Concept A (pack high flow mode with dual outflow valves) is estimated to cost about $380,500,000 to retrofit the current U. S. fleet and future production through 1992.

- Concept B (ram ventilation with added dump valve) is estimated to cost about $587,400,000 to retrofit the current U. S. fleet and future production through 1992.

8.4 EQUATION VALIDATIONS: Equation sets for all of the scenarios in this study have been derived to predict the smoke venting effectiveness of current airplanes and the proposed concepts. Some of the equation sets are partially validated for current airplanes by the results of past fires and airplane tests. The other equation sets, especially for forward smoke scenarios with the aft outflow valve open, are essentially not validated.

8.5 CONCEPT A: Contrary to earlier expectations, Concept A is predicted to provide small and only slightly significant smoke venting improvement compared to current airplanes.

8.6 CONCEPT B: Concept B is predicted to provide the following smoke venting improvements compared to current airplanes:

- Small and only slightly significant improvement during cruise and sea level operation with engines ON.

- Large improvement during sea level operation with engines OFF. This improvement is concluded to be of limited significance because past fire experience in current airplanes (without Concept B) shows that the smoke cloud spreading after ventilation shutoff is slow enough to allow successful passenger evacuation if the engine shutoff occurs just before the evacuation begins.

8.7 PAST FIRES: The improved smoke venting predicted for Concepts A and B would have been negated by the reported flight crew actions and/or the fire damage in the past fires on the Varig 707, Saudi L-1011 and Air Canada DC-9 airplanes.

8.8 CURRENT FLEET: During inflight fires similar to the past fires on the Varig 707, Saudi L-1011 and Air Canada DC-9 airplanes, a majority of the passenger cabin length is predicted to be free of smoke while the air conditioning systems of the current U.S. fleet are kept operating.

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